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VULNERABILITY OF INLAND WATERWAY TRANSPORT AND WATERWAY MANAGEMENT ON HYDRO-METEOROLOGICAL EXTREMES

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Deliverable 9.1	**Vulnerability of Inland Waterway Transport and Waterway Management on Hydro-meteorological Extremes**
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Abstract	The report (D9.1) deduces the significant vulnerability of Inland Waterway Transport (IWT) from the interaction of the waterway characteristics and the hydro-meteorological conditions in Central Europe. The study area covers the large inland waterways and the corresponding hydrological catchments of the River Rhine (one of the most-frequented waterways worldwide), the River Danube up to gauge Nagymaros in Hungary and the River Elbe. This study consists of four main components: 1) a compilation of the navigation conditions on the aforementioned waterways with focus on the main bottlenecks, 2) a systematic review of the mechanisms of vulnerability of water bound transportation, 3) a detailed analysis of the hydro-meteorological conditions identifying hydrological and hydro-meteorological criteria causing relevant extremes (floods, low flows, river ice) and 4) an

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	analysis of user requirements to improve navigation-related forecasting as important measure to mitigate vulnerability of IWT due to hydro-meteorological impacts on different time scales (short-term up to seasonal). The user-needs related to forecasting have been identified in close collaboration (within workshops and interviews) with current forecast users, potential users and stakeholders representing logistic companies, industrial enterprises, transmission network operators, waterway management authorities / ministries and intergovernmental organizations. The result of this report establishes a solid basis for the development of improved as well as new forecast products for IWT (D9.4) and the user-oriented assessment of forecast information within IMPREX (D9.2, D9.3).

Dissemination level of this document

X	PU	Public
	PP	Restricted to other programme participants (including the Commission Services)
	RE	Restricted to a group specified by the consortium (including the European Commission Services)
	CO	Confidential, only for members of the consortium (including the European Commission Services)

Versioning and Contribution History

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Table of Contents

List of figures

IMPREX has received funding from the European Union Horizon 2020 Research and Innovation Programme under Grant agreement N° 641811

IMPREX has received funding from the European Union Horizon 2020 Research and Innovation Programme under Grant agreement N° 641811

List of tables

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Glossary

Cargo	objects (produce, product) that are carried
Cargo volume	sum of goods / products quantifiable in units
Climatic Water Balance	Climatic water balance (CWB) is defined as the residuum from precipitation and potential evaporation. Positive values of the climatic water balance means that more water is supplied as needed (storages in the catchment are filled by the surplus), negative values indicate consumption of the available soil moisture by evapotranspiration.
Deadweight	is the carrying capacity of a vessel (difference in weight between a fully loaded and empty vessel). It includes cargo (payload), fuel, water, lubricating oil, crew, and provisions
DoRIS	RIS for the Austrian stretch of the Danube waterway (DoRIS = Donau River Information Services)
Draught	*Draught* total of a vessel in motion = draught loaded + squat. *Draught loaded* – the distance between the lowest point of the bottom of a loaded vessel when stationary and the water surface
ELWIS	RIS for the German waterways (ELWIS = Elektronischer Wasserstraßen-Informationsservice)
ENR	Etiage navigable et de regularization (see Low Navigable Water-Level LNWL)
Fairway	the part of a waterway in which specific widths and depths are maintained to enable continuous navigation
Flow duration curve	graph of river flow plotted against the exceedance frequency. It is generally derived from all flow values of a selected period.
GlW	equivalent low water-level (GlW = "Gleichwertiger Wasserstand") low flow reference water-level used for waterway maintenance

	on the River Rhine and Elbe, which is not exceeded on 20 ice-free days on average
GlQ	Flow rate associated with GlW
IWT	Inland Waterway Transport
HSW I / HSW II	Highest Navigable Water-Level (HSW = Höchster Schifffahrtswasserstand) leading to restrictions (HSW I) or suspension (HSW II) of navigation on a specific waterway stretch.
HNWL	Highest Navigable Water-Level (see HSW)
LNWL	Low Navigable Water-Level (LNWL, ENR, RNW) is a low flow reference water-level used for waterway maintenance on the River Danube, which is exceeded on 94% (i.e. on 343 days) of the ice-free days on average
Load factor	extent of goods loaded expressed as a percentage of the maximum possible loading of a cargo vessel
Means of transportation	conveyance to perform transport, usually self-propelled; the most dominant means of transportation are road transport, railway, ship and aviation
Modes of transportation	see: means of transportation
Multi-modal transport	transport where complete transport units (e.g. containers) are carried by at least two different means of transportation along the route
NM7Q	Annual lowest seven-day mean flow. The daily flow record for the gauges is analysed for the lowest moving average flow over 7 consecutive days in each year
Payload / Load Capacity	sum of goods put together for one trip, excluding fuel, water, stocks, etc. Usually the terms “load” and “load capacity” refers to the payload

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RIS	services designed to optimise the traffic and transport process and to support safe and efficient navigation on inland waterways (RIS = River Information Services)
RNW	Regulierungsniedrigwasserstand (see Low Navigable Water-Level LNWL)
Shipping company	a (large) enterprise carrying out transportation using its own and/or third party vessels
Squat	is a hydrodynamic effect of a ship in motion causing additional sinkage of a ship compared to its stationary condition
Transport	movements of goods in one or more trips using one or more means of transportation
Transport chain	technical and organisational linkage of transportation activities
Trip	movement of a means of transportation between the point of departure and the point of destination
Water Year	continuous 12-month period selected to present data relative to hydrologic or meteorological phenomena during which a complete annual hydrologic cycle normally occurs. For low flow analysis the water year from 1st April – 31st March is used, for high flow analysis the water year between 1st November and 31st October is used here. The different definitions are applied to avoid a split of annual low / high events at the turn of the year.

1 Introduction

Main findings

- Central Europe possesses a wide waterway network allowing all important industrial areas and the major sea ports to be reached via Inland Waterway Transport (IWT).
- The main hydrological impacts on IWT are floods, low stream flows and river ice with low flows causing the major threat.
- Hydro-meteorological and hydrological forecast products as part of River Information Services (RIS) are an important tool to increase operating efficiency and strategic management of IWT.

The European inland waterways offer a more than 40,000 km network of canals, rivers and lakes connecting cities and industrial regions across the continent. The European waterway network is particularly dense in the north-western part of the continent where the large waterways (especially Rhine, Danube, Elbe) in combination with their tributaries and canals enables inland shipping to reach many destinations and, for example, to travel from the North Sea to the Black Sea (Figure 1). All important industrial areas in Central Europe as well as the major sea ports (like Rotterdam, Antwerp, Hamburg) are accessible to inland shipping vessels (EU 2013).

Similar to other modes of transportation Inland Waterway Transport (IWT) depends on exogenous factors. Besides the socio-political situation, IWT is particularly affected by a number of natural environmental conditions.

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Figure 1: The Central European inland waterway network with its main transport corridors (Modified source: German Federal Ministry of Transport and Digital Infrastructure, Fachstelle für Geoinformation Süd, Regensburg, Germany)

During the last years a large number of European projects covered the topic of assessing the impacts and consequences of extreme weather events on transport system and the IWT in particular, as well as the possible changes of extremes due to climate change. The European FP7 project "ECCONET - Effects of climate change on the inland waterway networks" (www.ecconet.eu) analysed the effect of climate change on the IWT network with a focus on the Rhine-Main-Danube corridor as a case-study (Nilson et al. 2012). The two FP7 sister projects of ECCONET: the "EWENT - Extreme Weather impacts on European Networks of Transport" (http://virtual.vtt.fi/virtual/ewent/index.htm) (Leviäkangas et al. 2011, Vajda et al. 2011, Kreuz et al. 2012) and "WEATHER - Weather Extremes: Impacts on Transport Systems and Hazards for European Regions" (www.weather-project.eu) (Doll et al. 2012) aimed at assessing extreme weather impacts on the European transport system and analysing the economic costs of more frequent and more extreme weather events on transport and on the wider economy and explores adaptation strategies for reducing them in the context of sustainable policy design. The goal of the FP7 project "MOWE-IT – "Management of Weather Events in the Transport System" (www.mowe-it.eu) (Siedl & Scheighofer 2014) was to identify existing best practices and to develop methodologies to assist transport operators, authorities and transport system users to mitigate the impact of natural disasters and extreme weather phenomena on transport system performance.

Following the results of these projects the main hydrological hazards concerning IWT in Europe are low stream flows, floods and river ice (Nilson et al. 2012). Further influences are fog and wind, but they don't constitute a significant obstacle to IWT: most vessels are equipped with radar so they are able to navigate even by reduced visibility and normally vessels are sufficiently stable in order to cope with strong winds (Leviäkangas et al. 2011).

The remaining major impacts (River ice, floods, low flows) are of different relevance depending on climate conditions (e. g. maritime influenced climate vs. continental climate) as well as characteristics of the waterway (e. g. free-flowing stretches vs. impounded rivers). **River ice** primarily occurs in waterways with low or nearly no flow velocities (canals, impounded rivers) and in areas with low air temperature over longer periods (like Scandinavia or Eastern Europe). Besides blocking the waterway and interrupting its trafficability, ice run can damage vessels and harm technical structures, like weirs, locks or harbour facilities (Ashton 1986, Carstensen 2009). Therefore river ice forecasts, indicating affected stretches as well as estimating ice thickness, are a valuable information in order to coordinate the operation of icebreakers (e.g. pooling the vessels at hot-spots), trying to clear the waterway as long as possible, as well as to take into account limitations of waterway availability (e.g. shifting transport to another mode). In most parts of Europe, river ice is relevant for shipping just over a limited period of the year, whereas the water-level – high as well as low – is the hydrological parameter influencing navigation most time of the year. On the River Rhine navigation has not been suspended due to ice since at least the 1970s (Nilson et al. 2012).

Floods affect rivers, regulated as well as free flowing, whereas they are often not relevant for canals due to missing natural inflows. Restrictions related to floods depend on the absolute water height as above a given level, river traffic is halted. Therefore the criteria applied for the evaluation of the severity of the high-water situation and its effect on transportation and the inland waterway infrastructure are related to the water-levels of the

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waterway. The most relevant ones are the Highest Navigable Water-Levels HSW I and HSW II (HSW = "Höchster Schifffahrtswasserstand"). The exceedance of HSW I (the lower navigational flood level) means that vessels have to reduce their speed (leading to longer travel times) and they are forced to travel within the fairway. If HSW II is reached or exceeded shipping along the waterway section concerned is prohibited. In addition to the protection of the infrastructure the security of navigation is the main motivation, because high flow velocities occurring during floods reduce the manoeuvrability of the vessels travelling downstream and increase the risk of vessel damage especially due to drift wood. Additionally the guaranteed clearance below bridges might become too low and limits the possible layer of containers. Therefore water-levels aren't solely relevant for the flood protection community but also for navigational user (Belz et al. 2013). Although the duration and frequency of occurrence of floods is significantly lower than low flows, floods could cause relevant costs with regard to IWT. For example the big floods in 1993 and 1995 caused costs due to failed proceeds of more than 25 million Euros in the international Rhine basin (Engel 1999). But from the navigational perspective floods are in general more harmful to the waterway infrastructure (possible damage to navigation signs, gauges, ramps, groynes etc.) than to waterway transport itself. Suspension of navigation due to high water accounts usually only for a few days in a year; however, significantly longer periods may also appear, depending on the waterway considered.

Restrictions caused by **low stream flows / droughts** occur in all free flowing waterways, as flow rates and water-levels are directly correlated and the inter-annual flow regime leads to corresponding water-level conditions. In canals and impounded rivers the water-level is determined artificially and therefore just indirectly affected by hydro-meteorological drivers. Here, water-levels might be affected during low flows when the operation rules of the canal / weirs don't longer allow for abstraction or retention of water. Unlike floods, there is no threshold beyond which navigation is prohibited due to low stream flows. It is the responsibility of each vessel's skipper to decide whether it is possible to travel within a given section of the waterway despite the reduced water depth. So, it's an individual evaluation of risk (in terms of safety and cost-effectiveness of the transport) given the intensity of the low flow situation, the ship as well as the cargo type and the destination of the transport. Low water-levels reduce the cargo-carrying capacity of inland waterway vessels and thereby increases costs per transport unit (Euro per ton). Also travel-times (due to speed reduction in order to minimize the dynamic sinkage of the vessels) and fuel consumption (due to increased power demand in shallow waters and extended travel times) are affected by low flows. At the same time the danger of ship-grounding or ship-to-ship collisions increases due to reduced depth and width of the fairway. As low flow situations occur more often than floods and as they are relatively long lasting (weeks or even months), they are regarded as the major threat to the reliability of IWT. The estimated damage in shipping caused by the extreme drought 2003 was, for example, about 91 million for the Rhine basin (Jonkeren et al. 2007). Those dependencies are reflected by the way current water-level forecasts for waterways are used by the waterway transport sector (Meissner & Klein 2016). Figure 2 shows the number of accesses per day (black dots) on the forecast (published via the German River Information platform ELWIS: www.elwis.de) for the gauge Kaub, which is one of the main bottlenecks of the River Rhine. It is obvious that decreasing water-levels increases the need for water-level forecast information. Also in case of water-levels tending to the highest navigable water-level (indicated as "HSW"), more users are interested than in case of medium water-levels offering sufficient water-depths to fully load the vessels. The link between user demand and economic sensitivity is visible in Figure 2, too. The transport costs increase with decreasing water-levels as well (blue dots), initially moderate, subsequently exponentially. At high water-levels, large-sized vessels have advantages (economy of scale), which inverses to disadvantages compared to smaller vessels at low fairway depths.

Within the EU-Horizon2020 project IMPREX "Improving Predictions and management of hydrological Extremes" (2015-2019) WP9 "Sectoral Survey Transport" evaluates how improved hydro-meteorological and hydrological forecast products increase operating efficiency and strategic management of the European transportation sector with special focus on IWT.

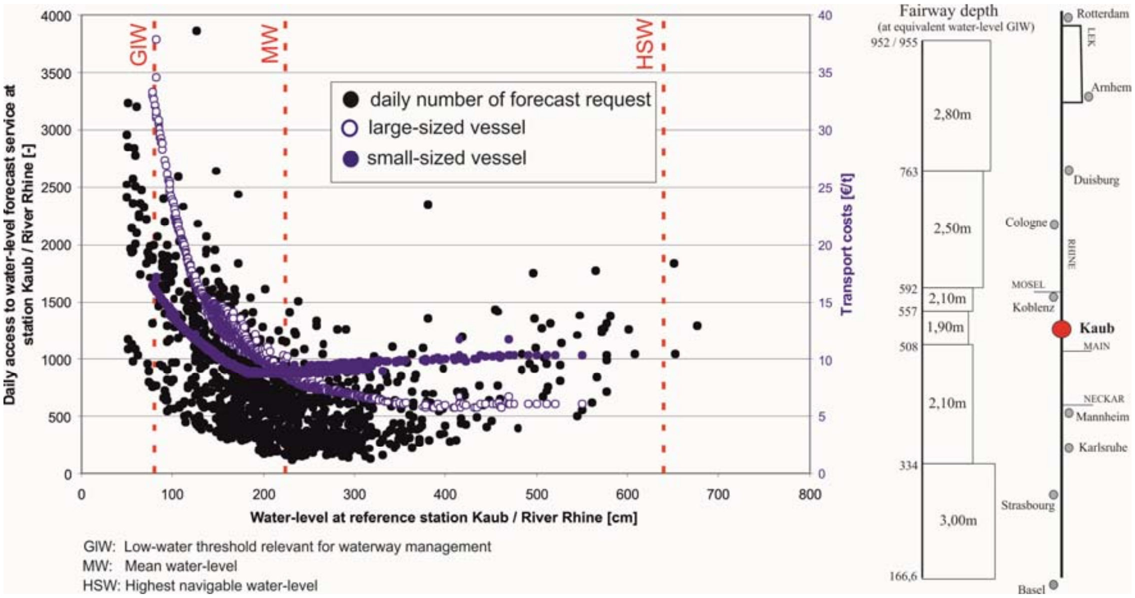

Figure 2: Number of daily users of the operational low flow forecast for the River Rhine at gauge Kaub (black dots) and simulated transport costs for two representative vessels (blue dots) both plotted against the absolute water-level. The right part shows the maintained fairway depth of the waterway Rhine (Meissner & Klein 2016).

This deliverable deduces the significant vulnerability of IWT from the interaction of the waterway characteristics and the hydro-meteorological conditions in Central Europe and assesses the user requirements to improve navigation-related forecasting as important measure to mitigate vulnerability of IWT due to hydro-meteorological impacts on different time scales (short-term up to seasonal). The deliverable is structured as follows: chapter 2 describes the study area covering the large inland waterways and the corresponding hydrological catchments of the River Rhine (one of the most-frequented waterways worldwide), the River Danube up to gauge Nagymaros in Hungary, and the River Elbe, chapter 3 gives an overview about IWT in Europe with special focus on Central Europe, chapter 4 compiles navigation conditions on the aforementioned waterways with focus on the main bottlenecks, chapter 5 gives a systematic review of the mechanisms of vulnerability of water bound transportation, chapter 6 identifies hydro-meteorological conditions causing relevant extremes (floods, low flows, river ice), chapter 7 assesses the impact of climate change on the vulnerability of IWT on hydro-meteorological extremes, chapter 8 assesses user requirements to improve navigation-related forecasting as important measure to mitigate vulnerability of IWT due to hydro-meteorological impacts on different time scales (short-term up to seasonal), results and main findings are concluded in chapter 9.

Please note: Different 12-month reference periods have been used for annual analysis of low flow and high flow events to present data relative to hydrologic or meteorological phenomena during which a complete annual hydrologic cycle normally occurs. For low flow analysis (annual number of days below selected water depths in chapter 4.5, annual NM7Q, annual number of days below defined quantiles of the flow duration curve in chapter 6.1) the water year from April 1 to March 31 is used; for high flow analysis (annual number of days exceeding the HSW-threshold in chapter 4.5 and 6.2, annual maximum flows in chapter 6.2) the water year between November 1 and October 31 is used here. The different definitions are applied to avoid a split of annual low / high events at the turn of the year.

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2 Study area

Main findings

- The sectoral survey “transport” within IMPREX focusses on water-bound transportation along the main Central European waterways Rhine, Elbe and Danube (up to gauge Nagymaros).
- The waterways considered represent different basin characteristics (like size, specific runoff) and flow regimes ranging from nival (snow-driven, e.g. Upper Rhine, Inn) to pluvial (rainfall dominated, e.g. Lower Elbe, Moselle, Main) including mixed regimes.

The study area of the sectoral survey transport in WP9 of the EU-Horizon2020 project IMPREX covers the large waterways and the corresponding hydrological catchments of Central Europe: waterway Rhine, Danube up to gauge Nagymaros in Hungary, and Elbe (see Figure 3). This catchments cover a major part of Central Europe and are situated in different hydro-climatic regimes (moderate maritime to the north, high mountain to the south and dry continental to the east).

The River Rhine with a total length of 1,230 km drains an area of approx. 200,000 km^2 with a mean flow rate of approx. 2,500 m^3/s (specific runoff 12.5 l/(s km^2)) at the mouth in the North Sea. It is shippable for large vessels between Rotterdam and Basel on a length of about 800 km. The River Elbe with a total length 1,090 km drains an area of approx. 150,000 km^2 with a mean flow rate of approx. 860 m^3/s (specific flow 5.7 l/(s km^2)). About 930 km are shippable between Pardubice in Czech Republic and the mouth in the North Sea at Cuxhaven. The River Danube with a total length of 2,826 km^2 drains an area of 817,000 km^2 with a mean flow rate of approx. 6,500 m^3/s (specific flow 8 l/(s km^2)) when reaching the Black Sea. It is shippable on a length of 2,415 km between Kelheim and the Black Sea. IMPREX concentrates on IWT in Central Europe. Hence the study area doesn’t cover the whole Danube, but the area up to gauge Nagymaros in Hungary with a catchment area of 184,000 km^2 and a mean flow rate of 2,340 m^3/s (specific flow 12.7 l/(s km^2)). The waterways Rhine and Danube are connected by the waterway Main and the Main-Danube-Canal, the waterways Rhine and Elbe are interlinked by the network of canals, like the Dortmund-Ems-Canal, the Mittellandkanal etc. (see Figure 1). Table 1 summarizes the main characteristics of the three basins.

The specific flows reflect the different hydro-climatic regions: the mountain climate influenced catchments of the River Rhine and the Upper Danube have considerable higher values than the dry continental climate influenced Elbe and Middle / Lower Danube.

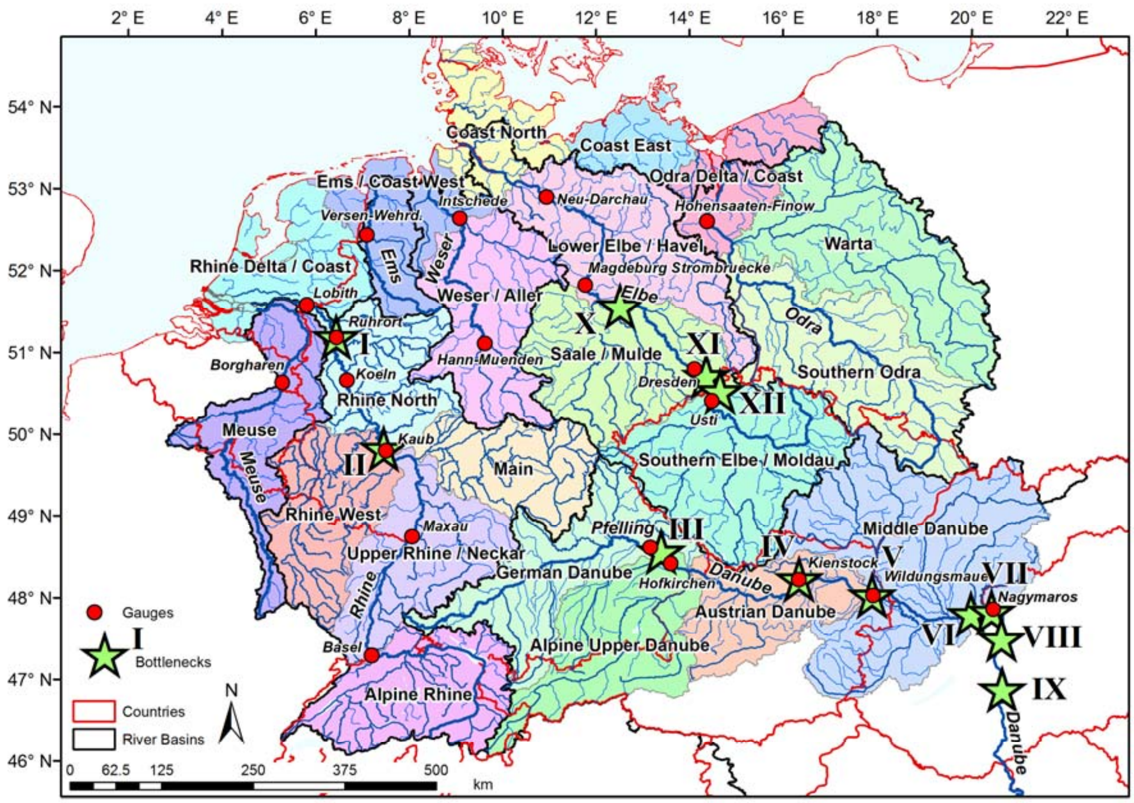

Figure 3: Map of Central Europe, climate regions used for hydro-meteorological analysis, relevant gauges, and important bottlenecks of the waterways Rhine, Elbe, and Danube.

The flow regimes present in the study area are characterised by interplay of nival (snow-driven) and pluvial (rain-driven) regimes. As indicated in Figure 4 the flow regime at gauge Maxau situated in the Upper Rhine shows a pronounced, single-peak mountain snow regime (nival). The early summer maximum flow slowly declines as a result of a superposition of high-mountain snow melt and summer storm water. The rainfall dominated (pluvial) flow regimes of the major tributaries of the River Rhine (Neckar, Main, Moselle river) superpose the snow dominated flow-regime of the Alpes and lead to complex flow regimes at the

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gauges Kaub and Ruhrort (Middle and Lower Rhine River, respectively) with relatively high flows during the winter months originating from high precipitation and low evaporation in the mid-mountain ranges of Germany and France. The low flows typically occur in late summer and autumn due to high evaporation and low melt water input from the Alpine tributaries. The flow regime at the gauge Hofkirchen, downstream the inflow of the Alpine river Isar in the Danube, shows a complex broad-peaked runoff regime from an overlapping of rainfall and snowmelt influence, a pluvio-nival regime. After the inflow of the Alpine river Inn, which shows a pronounced nival flow regime, the flow regime in the River Danube changes to a nival regime, which is obvious at the gauges Kienstock and Nagymaros. The Elbe gauges Dresden, Mageburg-Strombrücke and Neu-Darchau show pronounced pluvial runoff regimes with maximum flows in late winter / spring and lowest flow values in late summer.

Table 1: Characteristics of the Rhine, Elbe, and Danube basin (Maurer et al. 2011, Blöschl et al. 2013, Konecsny & Nagy 2014)

	Rhine Basin	Elbe Basin	Danube Basin
Catchment Area	197,000 km²	148,268 km²	817,000 km² Nagymaros: 183,534 km²
River Length	1,230 km	1,094 km	2,826 km
Inhabitants	58 Mio.	24 Mio.	83 Mio
Countries (sorted by catchment shares)	DE, CH, NL, FR, LU, BE, AT, LI, IT	DE, CZ, AT, PL	RO, H, YU, AT, DE, SK, BG, BIH, HR, UA, CZ, SLO, MD, CH, I, PL, AL, MK
Mean Flow (MQ)	Mouth: ~2,500 m³/s Border DE/NL: ~2,390 m³/s	Mouth: ~860 m³/s Border CZ/DE: ~310 m³/s	Mouth: ~6,500 m³/s Border DE/AT: ~1,420 m³/s Nagymaros: ~2,308 m³/s
Highest Flow (HHQ)	Border DE/NL ~12,000 m³/s (1926)	Border CZ/DE: ~5,350 m³/s (1845)	Border DE/A: ~10,000 m³/s (2013) Nagymaros: 9,790 m³/s (1891)
Lowest Flow (NNQ)	Border DE/NL: ~575 m³/s (1929)	Border CZ/DE: ~20 m³/s (1954)	Border DE/A: ~350 m³/s (1972) Nagymaros: ~531 m³/s (1894)
Runoff-/Catchment share/Ratio	DE ~47 % / ~55 % / 0.85 CH ~40 % / ~15 % / 2.67 FR+LU ~12 % / ~30 % / 0.40	CZ ~36 % / ~34 % / 1.06 DE ~64 % / ~66 % / 0.97	DE ~11 % / ~ 7 % / 1.6 AT ~21 % / ~10 % / 2.1
		Water Balance	
Precipitation	~950 mm	~630 mm	~785 mm (DE: ~970 mm)
Evapotranspiration	~550 mm	~450 mm	~515 mm (DE: ~510 mm)
Runoff	~400 mm	~180 mm	~270 mm (DE: ~460 mm)

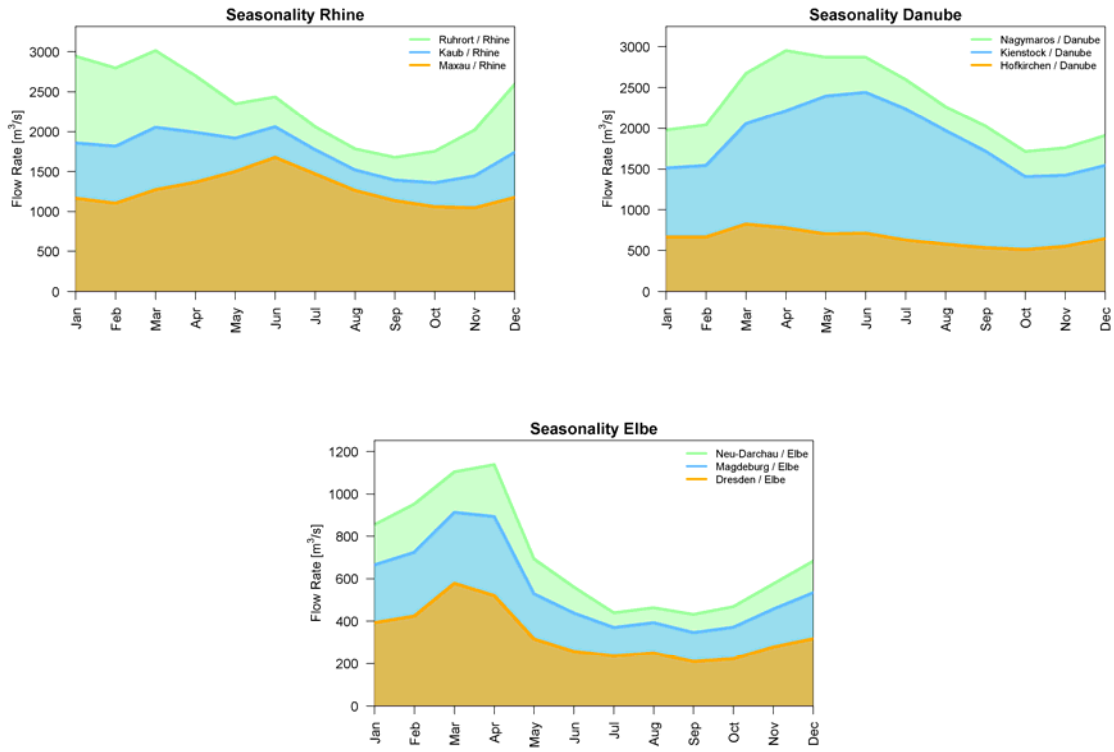

Figure 4: Flow regimes at selected gauges in the Rhine, Danube, and Elbe Basin given as the mean monthly flow rates based on observed data of the period 1981-2010

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3 Inland waterway transport in Europe

Main findings

- The River Rhine is Europe's most important inland waterway (carrying approximately 2/3 of the European IWT volume), followed by the north-south corridor (the Netherlands, Belgium and northern France) with a portion of ~ 20 % and the east-west axis (canal system between Ruhr and Elbe / Odra, ~ 12%) and the Danube / south-east axis (~ 10 %).
- The volume of goods carried on European inland waterways is relatively stable; even a positive annual growth rate (of + 1,5 %) could be observed since 2010 for IWT.
- The strengths of IWT lie mainly in its ability to convey large quantities of goods per vessel, its low transport costs and its environmental friendliness. In addition, it has a high level of safety, low infrastructure costs and still free capacity.
- The major weaknesses of this mode of transport are its dependence on the variable fairway conditions in free-flowing river stretches and the associated variable load factor of the vessels as well its comparatively low transportation speed.

A common structuring of the most significant European waterways is to distinguish between the Rhine / Rhine-Alps corridor, the north-south axis, the Danube / south-east axis and the east-western axis (CCNR 2016). The Rhine-Alp corridor covers parts of the Netherlands, Germany, France, and Switzerland. The main navigable waterway of this area is the Rhine itself from Switzerland to the German-Dutch border, where almost 200 millions tons are transported per year (approximately 2/3 (!) of the European IWT volume). So the River Rhine is Europe's most important inland waterway and therefore it is a focal point of IMPREX. The north-south axis (comprising the Netherlands, Belgium and northern France) is the second most important shipping axis in Europe. Here almost 20 % of the total Europen transport volume on inland waterways is carried. This region is characterized by a very dense network of natural and artificial waterways. The majority of transport is carried by cross-border traffic between the Netherlands and Belgium.

Navigation on the Danube constitutes the main part of Europe's south-east transport axis between Western, Central and South-Eastern Europe up to the Black Sea. Approximately

10% of the European IWT volume is currently handeled along this axis. Although the Danube fulfils a valuable function as a mode of transport especially for the agricultural and foodstuffs sector, it has not yet been exploit the full potential as a main traffic axis which is desirable from a pan-European perspective (CCNR 2016). The east-west axis connects the Rhine-Ruhr region with the Elbe, the area of Berlin and the Odra. Its main waterway is the Mittellandkanal, Germany's longest canal with a length of 321 km. The transport volume in this corridor is with approximately 12 % comparable to the one of the Danube. Figure 5 depicts the share of Europe's total IWT volume amongst the four aforementioned main axis.

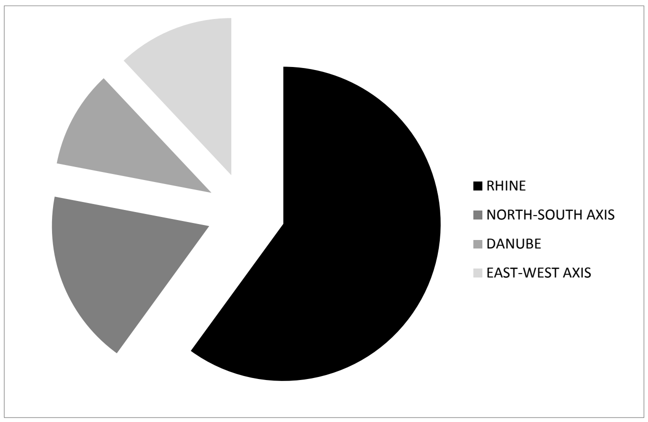

Figure 5: Percentage of European IWT volumes (annual total amount of approximately 550 million tons)

The next Figure 6 visualizes the extraordinary importance of the Rhine corridor by scaling the width of the waterway in this map by the annual transport volume. The thicker the line for a specific waterway is the more goods are transported along this stretch. In red the transport volume of the tidal / maritime waterways is indicated showing the importance of the port of Hamburg (situated approximately 120 km upstream the Elbe River) as one of Europe's biggest seaports (besides Rotterdam and Antwerp). Figure 7 shows the freight transport on the Danube within the different countries between Germany and Romania where the river flows into the Black Sea.

IWT is particularly suitable for the transport of large quantities of cargo, especially bulk cargo and containers. A standard inland shipping vessel with a length of 135 metres can carry up to 3,800 tonnes, which is equal to nearly 150 lorries. The volume of goods carried on European inland waterways is relatively stable over a multi-year period. Between 2010

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and 2015 (= period starting with the recovery from the economic crisis) even a positive annual groth rate of + 1.5 % for IWT is observed (CCNR 2016). The Netherlands, Germany, and Belgium are the major inland shipping nations in the EU: about 80% of the total IWT volume in Europe is carried on the territory of these three countries. By modal share, the Netherlands, Romania, and Bulgaria have most goods carried by inland shipping. In Poland and the Czech Republic, volumes are going upward again after a declining trend (INE 2016).

While the overall amount of goods is relatively stable, there is a structural change going on. Using the example of the River Rhine the goods that dominated transport 20 years ago, namely ores, petroleum products and building materials, have posted a 35% decline over the past 20 years. Nevertheless they still form approximately half of the goods transported on the River Rhine. At the same time there has been a 95% increase in the carriage of other goods such as containers, chemical products and coal over this same twenty-year period (CCNR 2016). While container transport is a growing market especially on the Rhine it isn't on the Upper Danube, the Elbe and the Odra. Europe-wide the agribulk business (agricultural bulk products, e.g. grain, animal feed, etc) is a also growing market over the last years and is expected to continue its upward trend (INE 2015).

Currently IWT has approximately a 7 % share of the freight volume in the EU. In light of an overall continuing transport growth within the European Union and the fact that other modes of transport increasingly suffer from congestion, capacity problems and delays there is a need to use the free capacity offered by IWT more forceful. IWT is a cost-efficient and environment-friendly mode of transport, with an excellent carbon footprint especially compared to road transport. IWT is also associated with a high degree of reliability and safety, as well as the lowest noise emissions being reflected in the lowest external costs related to one ton of cargo transported over one kilometre, compared with other modes of transport. Strengthening IWT requires a good waterway infrastructure and an optimized handling of the dominant natural / hydrological impacts on inland navigation.

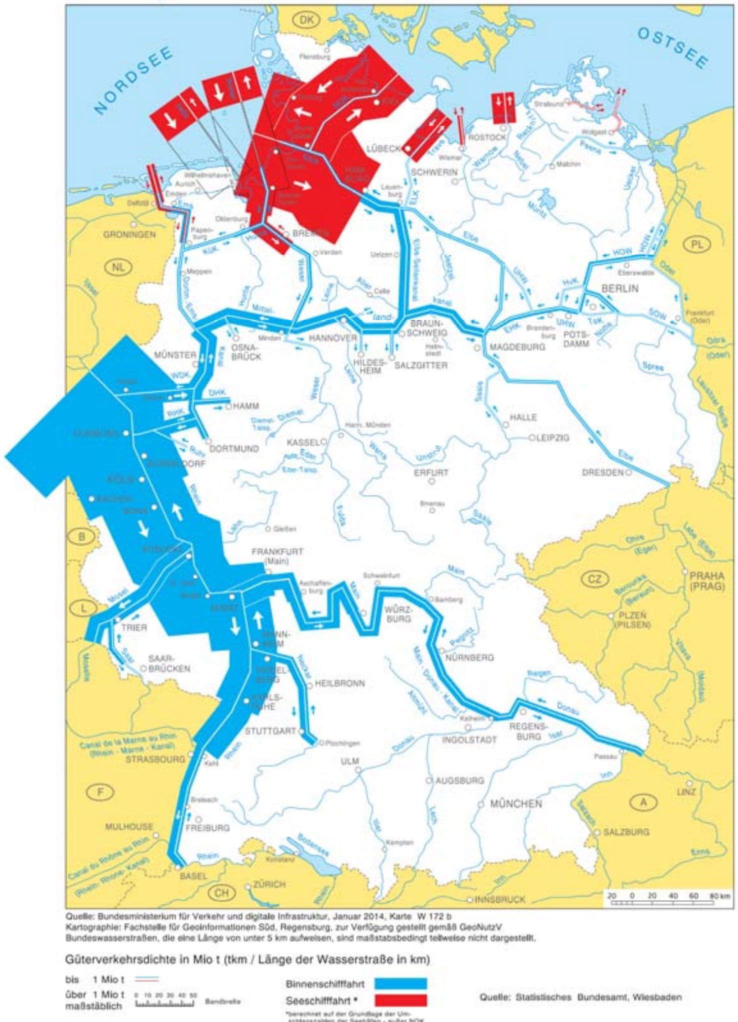

Figure 6 Density of freight traffic on the German waterways (situation in 2010), (source: German Federal Ministry of Transport and Digital Infrastructure, Fachstelle für Geoinformation Süd, Regensburg, Germany)

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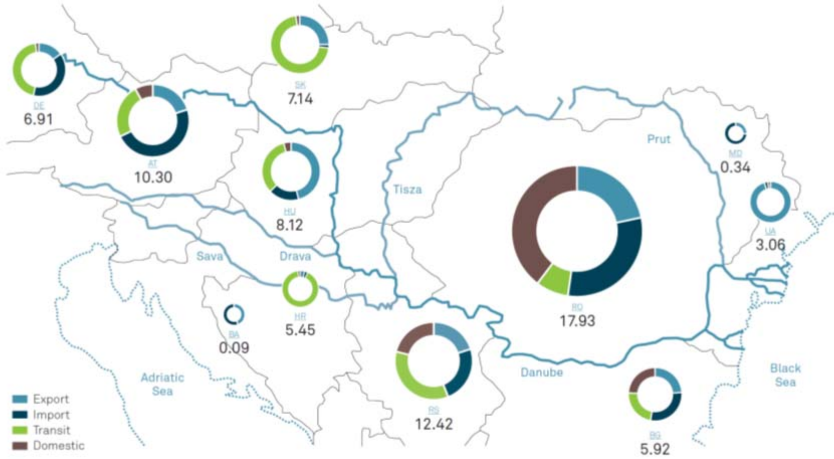

Figure 7: Freight transport in million tons on the entire Danube (situation in 2014), (ViaDonau 2016a)

4 Navigation conditions

Main findings

- Waterways are classified (classes I to VII) based on the maximum dimensions of vessels which are able to operate on the specific waterway; waterways meeting at least the requirement of class IV can be considered as inland waterways of international importance in the Pan-European network ("E waterways"), like Rhine, Danube and Elbe.
- Infrastructural bottlenecks – sections of waterways that restrict or hinder continuous navigation – still exists and are focal points for waterway management as well as for navigation-related forecasting.
- The navigational conditions differ between Rhine, Elbe and Danube. Especially the Elbe offers significantly less water-depths and vessel draught respectively than the Danube or the Rhine. The latter offers, even at the gauge Kaub, representing one of the bottlenecks, water-depths of 2.5 to 3.5 meters most time of the year and therefore – with regard to this criterion – comparatively good conditions for navigation.
- Looking at the floods the differences between the waterways are less pronounced. The HSW-value at the Danube (gauge Hofkirchen) is exceeded most frequently compared to Rhine and Elbe; at the Elbe navigation is interrupted less often than at Rhine or Danube, but in case of a flood the suspension of navigation normally persists over a longer period.
- The load factor, indicating to which percentage the different ship types could have been load, shows comparable results and emphasize the natural variations of the navigation conditions again.

The aim of the "*European Agreement on Main Inland Waterways of International Importance (AGN)*" (UNECE 1996) signed in 1996 is to facilitate and develop international transport by inland waterways in Europe. The agreement defines technical and operational characteristics of inland waterways of international importance. Only waterways meeting at least the requirement of class IV can be considered as inland waterways of international importance in the Pan-European network or simply "E waterways". The waterway class determines the maximum dimensions of vessels which are able to operate on the specific waterway. The classes range from I (only usable by smaller vessels) to VII (see Table 2).

It recommends a minimum possible vessel draught of 2.50 m, available at least 240 days on average per year on waterways with fluctuating water-levels (Annex III). However, for upstream sections of natural rivers characterized by frequently fluctuating water-levels due to strong direct dependence of weather conditions, it is recommended to refer to a period of at least 300 days on average per year. No breaks shall occur due to low water and the duration of breaks in the navigation period caused by natural phenomena such as ice, floods, etc. should be kept to a minimum by appropriate technical and organizational measures. A minimum draught of 1.20 m should be available at all times.

As a follow-up of the AGN the "*Inventory of Main Standards and Parameters of the E Waterway Network (Blue Book)*" (UNECE 2012) shows the current status of inland navigation infrastructure parameters in Europe. The most important bottlenecks for inland navigation on the waterways Rhine, Danube and Elbe mentioned in the "Blue Book" are shown in Figure 3. The "Blue Book" also includes information about the waterway classes for specific waterways in Europe: the waterway Rhine is classified as class VI (a-c depending on the section) (see Figure 8), the waterway Danube is classified as Vb in the German part of the Danube up to Regensburg, VI (a-c) in the section Regensburg to Belgrade and VII afterwards (see Figure 9), the waterway Elbe is classified as VIb downstream of Wittenberge, Va from Wittenberge to Ústi nad Labem in Czech Republic and in the canalized stretches upstream of Usti as class IV (see Figure 8).

Figure 8: Waterway classes of the German Waterways and possible dimensions of the vessels and convoys according to the class (modified source: German Federal Ministry of Transport and Digital Infrastructure, Fachstelle für Geoinformation Süd, Regensburg, Germany)

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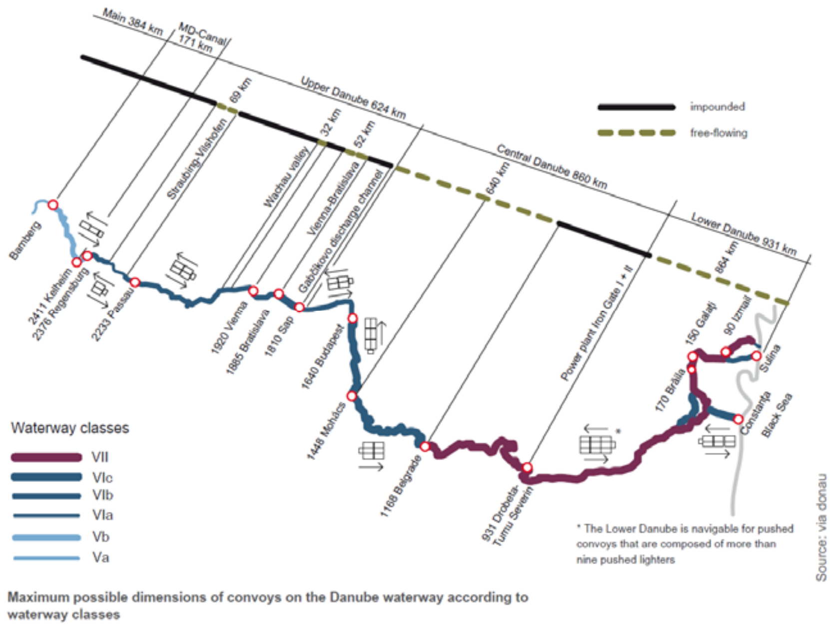

Figure 9: Waterway classes of the Danube waterway (ViaDonau 2013)

Table 2: Waterway classes according to the classification of European inland waterways and maximum dimensions of motor cargo vessels and pushed convoys

Waterway class	Designation / Formation	Max. Length L [m]	Max. Width B [m]	Draught d [m]	Deadweight [t]
		Motor Cargo Vessels			
IV	Johann Welker	80-85	9.5	2.5	1,000 – 1,500
Va,b; VIa	Large Rhine Vessel (e.g. GMS-95, GMS-110)	95-110	11.4	2.5 – 2.8	1,500 – 3,000
VIb,c; VII	Large Rhine Vessel (e.g. GMS-135, JOWI)	140	15	3.9	1,500 – 3,000
		Pushed Convoys			
IV		85	9.5	2.5 - 2.8	1,250 - 1,450
Va		95 - 110	11.4	2.5 - 4.5	1,600 – 3,000
Vb		172 - 185	11.4	2.5 - 4.5	3,200 – 6,000
VIa		95 – 110	22.8	2.5 - 4.5	3,200 – 6,000
VIb		185 – 195	22.8	2.5 - 4.5	6,400 – 12,000
VIc		270 – 280	22.8	2.5 - 4.5	9,600 – 18,000
		195 - 200	33 – 34.2	2.5 - 4.5	9,600 – 18,000
VII		275 - 285	33 – 34.2	2.5 - 4.5	14,500 – 27,000

4.1 Reference water-levels

For waterway management different low flow reference water-levels are defined in the study area. These reference water-levels are often associated with fairway depths that are regarded as target for waterway management. On the River Rhine the so called "equivalent water-level" (GlW = "Gleichwertiger Wasserstand") is applied. This threshold is associated with a flow rate (GlQ) which is exceeded on 345 days per year in the long-term mean (without days with river ice). Statistically, this value is comparable to the 95th percentile of the long-term flow-duration curve. GlW-definition is close to the so called "Low Navigable Water-Level" (LNWL) ("Regulierungsniedrigwasserstand" (RNW), "Etiage navigable et de regularization" (ENR)) that is commonly used on the River Danube, which is exceeded on 94% (i.e. on 343 days) of the ice-free days on average. The definition of the underlying reference period of GlW, LNWL differs between waterways and even country sections of the same waterway. On the River Rhine a period of 100 years is used for most gauges (for GlW2012) to derive GlW, while the LNWL on the Danube is based on a 30 year period.

The current valid low flow reference level at the waterway Elbe is the GlW1989*. The definition is similar as for the River Rhine (i.e. exceeded on 345 ice-free days per year in the long term mean) but it was derived from selected years of the period 1973 – 1989 and not from all years of a reference period.

High flow can lead to restriction or suspension of navigation. The level of restriction is officially regulated (e.g. Danube Commission 2006, WSV 2011) and depends on the water-level. For the River Rhine, two "Highest Navigable Water-Levels" (HSW) are defined with respect to selected gauges. The first, lower threshold (HSW-I) stops selected ship types and limits the speed of the remaining ships. It also concentrates traffic in the centre of the fairway to reduce wave stress on the lateral infrastructure. The second, higher threshold (HSW-II) normally leads to stoppage of navigation. In addition to the protection of the infrastructure the security of navigation is a motivation here. High flow velocities associated with water-levels above HSW-II reduce the manoeuvrability of the vessels travelling downstream. There is also the danger that flotsam (especially tree trunks) damage vessels and trigger accidents. Additionally at some locations the specified clearance below bridges crossing the waterway could not be guaranteed anymore due to the high water-levels. At the German parts of the waterways Elbe and Danube one HSW value, which exceedance

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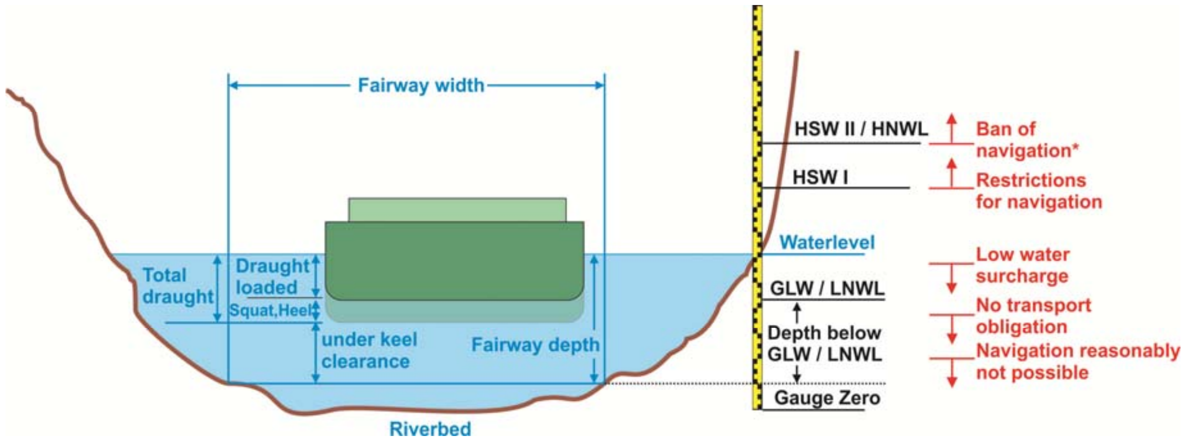
leads to stoppage of navigation, is defined. In the Austrian part of the Danube the HNWL is defined as the water-level reached or exceeded at a Danube water gauge on an average of 1% of days in a year (i.e. on 3.65 days) over a reference period of several decades (excluding periods with ice) (ViaDonau 2016a). If the HNWL is reached or exceeded by a certain degree, the navigation may be suspended for reasons of traffic safety. Generally navigation is suspended in Austria by an exceedance of HSW + 90cm (ViaDonau 2016a).

Table 3 shows the reference levels and the corresponding flow rates for important gauges of the waterways Rhine, Danube, Elbe.

Table 3: Reference water-levels for important gauges of the waterways Rhine, Danube, and Elbe. Equivalent water-level GlW, low navigable water-level LNWL, highest navigable water-levels HSW/HNWL, flow rate at GlW/LNWL Q(GlW/LNWL), and flow rate at HSW/HNWL Q(HSW/HNWL)

Gauge	Waterway	GlW/LNWL	HSW/HNWL	Q(GlW/LNWL)	Q(HSW/HNWL)
Kaub	Rhine	78	640	784	5138
Ruhrort	Rhine	233	1130	1028	10869
Pfelling	Danube	290	620	211	1246
Hofkirchen	Danube	207	480	324	1560
Kienstock	Danube	164	618	930	4870
Wildungsmauer	Danube	162	564		
Nagymaros	Danube	4	448		
Dresden	Elbe	97	500	128	1220
Magdeburg	Elbe	100	550	233	2560

The reduced loading capacity of ships leads to increased costs during low flow periods. To compensate the disproportionate increase in costs additional charge (Low Water Surcharge) are defined for several low water-levels for several gauges at the waterway Rhine and Danube. Below a certain low water threshold there is no longer an obligation to transport (CONTARGO 2015). Figure 10 illustrates the different reference water-levels together with the main fairway parameters.



*In Austria navigation is generally banned at water-levels > HSW + 90 cm

Figure 10: Fairway parameters, draught and reference water-levels

4.2 Bottlenecks waterway Rhine

Figure 11 shows the guaranteed fairway depths below the GlW on the waterway Rhine. The main shippable tributaries of the River Rhine are impounded with minimum water depths: Mosel 3 m, Main 2.90 m up to lock Lengfurt and 2.50 m from Lock Lengfurt to the Main-Danube-Canal (depth 2.70 m), Neckar 2.80 m. The relevant limiting sections for the load of the vessels and convoys are dependent on the routes. For the route Rotterdam to the port of Duisburg the section downstream of gauge Duisburg-Ruhrort (bottleneck I in Figure 3) is relevant. This is one of the strategic bottelnecks defined by the United Nations Economic Commission for Europe (UNECE 2012) with fairway depths of 2.80 m below GlW (reference gauge Ruhrort) because the water-level there limits especially the number of layers of container ships heading to Duisburg. For the route Rotterdam to the Moselle River and the Rhine ports between Duisburg and Koblenz the section between Ruhrort and Koblenz is load limiting. The most important bottleneck of the River Rhine for ships heading to the Upper Rhine as well as to the Main and Neckar waterways is the section between St. Goar and Mainz (bottleneck II in Figure 3) with available fairway depths of 1.90 m below GlW (reference gauges Kaub and Oestrich). Traditionally the gauge Kaub has been used by navigation to estimate the available fairway depth for the aforementioned stretch in the Middle Rhine area. To this day Kaub is the gauge for which the vast majority of requests of water-level forecasts during medium and low flows periods occur. That's why Kaub is used in several analysis presented in this report as a representative gauge of the River Rhine. The

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German Waterway and Shipping Administration points out that skipper should (also) look at gauge Oestrich, situated 60 km upstream of Kaub near the mouth of the Main, when passing this waterway stretch. In this upstream part of the bottleneck, called "Rheingau", the shape of the river is less narrow than more downstream at Kaub. Therefore the water-levels at Oestrich are less sensitive to changes of the flow rates which might lead to an overestimation of the available depths of the section between St. Goar and Mainz especially in case of rising water-levels above mean water. So, Oestrich is a relevant gauge for navigation, too, but most of the waterway users seem to base their decisions on the gauge Kaub and its corresponding forecasts. The elimination (also with structural measures) of the bottleneck in the Middle Rhine (bottleneck **II** in Figure 3) is one of the waterway projects with top priority (BMVI 2016)

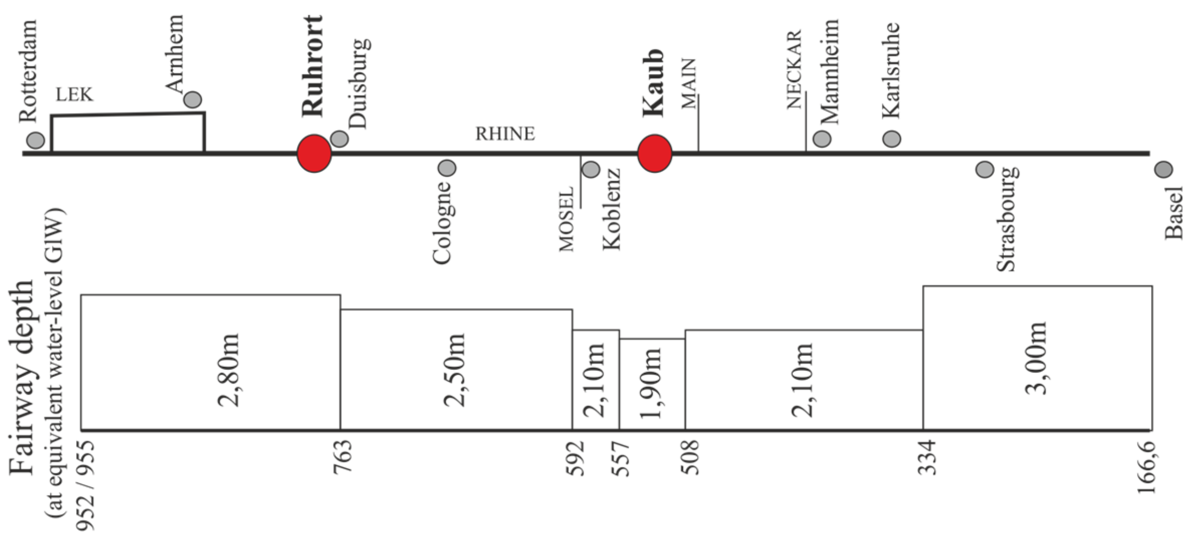

Figure 11: Waterway profile of the Rhine, guaranteed fairway depth below equivalent water-level GlW

4.3 Bottlenecks waterway Danube

With the new "Recommendations on Minimum Requirements for Standard Fairway Parameters, Hydrotechnical and Other Improvements on the Danube" valid as from 01.01.2013 published by the Danube Commision (Danube Commission 2012) minimum fairway depths should be provided in such a way that safe navigation with a vessel draught loaded of min. 2.50 m is possible on 343 days per year on average (Definition of the LNWL).

As there are no guaranteed minimum fairway depths at LNWL on the Danube (with the exception of the German section of the navigable Danube), the load of the vessels has to be decided by the operators based on currently available fairway depths published on river and fairway information services (http://www.danubeportal.com/, http://www.doris.bmvit.gv.at/, http://www.hydroinfo.hu/ for the critical sections in the study area).

The Fairway Rehabilitation and Maintenance Master Plan for the Danube and its navigable tributaries (Danube Region Strategy 2014) highlights all critical locations and the required short-term measures to ensure proper fairway maintenance. As a follow-up a first set of National Action Plans has been elaborated in line with the ministerial conclusions of 3rd December 2014 by which the Fairway Rehabilitation and Maintenance Master Plan was endorsed (Fairway Danube 2016).

In the impounded sections of the German part of the navigable Danube a minimum fairway depth of 2.90 m (up to barrage Straubing) and 2.70 to 2.80 m in the impounded section Vishofen to Jochenstein is available. In the free flowing section between Straubing and Vilshofen (bottleneck **III** in Figure 3) a fairway depth of 2.0 m is maintained (reference gauges Peffling upstream and gauge Hofkirchen downstream the river Isar mouth). In the EU funded project (2007-DE-18050-S) "Independent variant research on the development of the Danube between Straubing and Vilshofen" interdisciplinary studies on the possibilities for improving the navigation conditions in this section based on different variants have been conducted. Elements of the Variant A: *"Further optimized status quo, conventional river training, sediment management"* to improve the available water depths during low flows by about 20 cm are currently in the plan approval procedure (BMVI 2016) (further project information in German: http://www.donauausbau.wsv.de/; http://www.lebensader-donau.de/).

The major part of the Danube is influenced by ten reservoirs of hydroelectric power plants. The major bottlenecks are the free-flowing section in the Wachau (river-km 2,038 to river-km 2,003, bottleneck **IV** in Figure 3) with minimum fairway depths of about 2.40 m (NEWADA Duo 2016) at LNWL (reference gauge Kienstock) and the section between Vienna and Bratislava (river-km 1,921 to river-km 1,878, bottleneck **V** in Figure 3) with minimum fairway depths of about 2,00 m (NEWADA Duo 2016) at LNWL (reference gauge Wildungsmauer). To secure adequate fairway conditions at low water-levels in the section East of Vienna and to stabilize the river bed the Federal Ministry of Transport, Innovation

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and Technology (bmvit) and via donau initiated the "Integrated River Engineering Project on the Danube to the East of Vienna" with pilot projects Bad Deutsch-Altenburg and Witzelsdorf (Simoner et al. 2012, ViaDonau 2016b).

There are several critical location in the Slovak / Hungarian stretch of the Danube (Danube Region Strategy 2014) in the free flowing stretch of the Danube downstream of the reservoir of the hydroelectric power plant Gabcikovo. The most critical section on the entire Slovak stretch is situated at the common Slovak / Hungarian stretch on river-km 1735.5 – 1733.7 (bottleneck **VI** in Figure 3) (Cenkov = Esztergom) between the mouth of the rivers Vah and Hron with minimum fairway depths of about 2.20 m (NEWADA Duo 2016) at LNWL (reference gauge Esztergom). Further bottlenecks in Hungary located in the study area of IMPREX (Figure 3) are the lower Dömös shallow section (river-km 1699.30 to river-km 1697.60 bottleneck **VII** in Figure 3) after the mouth of the river Ipel with minimum fairway depths of about 1.90 m (NEWADA Duo 2016) at LNWL (reference gauge Nagymaros), the Budafok shallow section (river-km 1638.60 to river-km 1637.10, bottleneck **VIII** in Figure 3) at Budapest Danube with minimum fairway depths of about 2.00 m (NEWADA Duo 2016) at LNWL (reference gauge Budafok), and the Solt shallow section downstream of Budapest (river-km 1558.5 to river-km 1557.5, bottleneck **IX** in Figure 3) with minimum fairway depths of about 2.00 m (160 m width) / 2.50 m (60 m width) (NEWADA Duo 2016) at LNWL (reference gauge Dunaföldvár).

Budafok and Solt shallow sections are outside the IMPREX hydrological modelling domain (up to gauge Nagymaros) but are listed here as the flow at Nagymaros also dominates the flow and water-level situations at Budafok and Solt.

4.4 Bottlenecks waterway Elbe

In the "*Inventory of Main Standards and Parameters of the E Waterway Network (Blue Book)*" (UNECE 2012) the whole German part of the inland waterway upstream of weir Geesthacht is a strategic bottleneck with low fairway depths in dry season (1.4 m). The target fairway depths at the GlW89* are 1.60 m in the section Geesthacht to Dresden (bottleneck **X** in Figure 3) and 1.50 m from Dresden to the German / Czech border (bottleneck **XI** in Figure 3). As there are no guaranteed fairway depths the load of the vessels has to be decided by the operators based on the currently available fairway depths published for 9 sections (see Table 4) along the German part of the Elbe (www.elwis.de).

In Czech republic the waterway Elbe is impounded up to the reservoir of Strekov near Ústi nad Labem with minimum fairway depths of 2.00 m downstream and 2.10 m upstream the Moldau mouth. The non-impounded section downstream of Strekov up to the German border is a critical section (bottleneck **XII** in Figure 3) with extremely low fairway depths during dry seasons. Large reservoirs in Czech Republic (e.g. Vltava / Moldau cascade) are used to increase low water-levels and to improve navigation conditions during low flow periods. For Czech Republic the waterway Elbe is of great importance as it is the only access to the sea ports and the European waterways. To improve the conditions in the free flowing part a lock at Decin near the German border is planned which triggered controversial discussions in both countries.

Table 4: Sections of the German Elbe for which fairway depths are published

Nr.	Section	Elbe-km	Reference gauge
1	Schoena to Dresden	0.0 – 56.8	Dresden
2	Dresden to Riesa	56.8 – 109.4	Dresden
3	Riesa to mouth Elster	109.4 – 198.6	Torgau
4	Mouth Elster to mouth Saale	198.6 – 290.7	Wittenberg
5	Mouth Saale to entry industrial harbour Magdeburg	290.7 – 332.8	Magdeburg Strombrücke
6	Entry industrial harbour Magdeburg to Niegripp	332.8 – 343.9	Rothensee
7	Niegripp to Muehlenholz	343.9 – 422.8	Tangermuende
8	Muehlenholz to Doemitz	422.8 – 502.25	Wittenberg
9	Doemitz to Lauenburg	502.25 – 569.2	Hohnstorf

4.5 Navigation conditions for selected critical locations

The following figures characterize the conditions of navigation along the free-flowing stretches of the international waterways Rhine (represented by gauge Kaub), Danube (represented by gauge Hofkirchen) and Elbe (represented by gauge Magdeburg). As for navigation purposes the water-depth is the relevant parameter in the end, Figure 12 to Figure 14 indicates on the one hand the number of days per year for which different water-depths (instead of water-levels) are not exceeded within the period 1981 to 2015 (left part).

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The depths range from 1.5 metres (about the minimum draught of a small-sized vessel like the Johann Welker-type) up to 4 metres (maximum draught of a large-sized vessel JoWi-class or a pushed convoy on Rhine / Danube). As fairway depths following values have been assumed:

- Rhine: Kaub 1.90 m and Ruhrort 2.80 below GlW
- Danube: Hofkirchen 2.00 m and Kienstock 2.40 m below RNW / LNWL
- Elbe: Dresden and Magdeburg Strombrücke 1.60 m below GlW1989*

On the other hand the aforementioned figures show the number of days per year with absolute water-levels above the HSW so that navigation had to be suspended (right part of the figures).

As the three figures reveal, the navigation conditions differ between the three waterways. Especially the Elbe (Figure 14) offers significantly less water-depths and vessel draught respectively than the Danube (Figure 13) or the Rhine (Figure 12). The Rhine offers, even at the gauge Kaub, representing one of the bottlenecks, water-depths of 2.5 to 3.5 meters most time of the year and therefore – with regard to this criterion – comparatively good conditions for navigation. At Hofkirchen / Danube water-depths above 4 meters are rare compared to the Rhine, but water-depths of 2.5 to 3.5 meters are available most time of the year, too. In contrast the dominating water-depth at Magdeburg / Elbe is 2 meters to 2.5 meters at maximum for the vast majority of years in the period 1981 to 2015.

But, of course, it is visible that the water-depth is a parameter considerably dynamic, even on the annual scale chosen here. Years with high water-depths on average (e.g. 1999 at the Rhine or 2002 at the Danube and Elbe) are followed by drier years, like the one of the extreme low flow events 2003 or 2015.

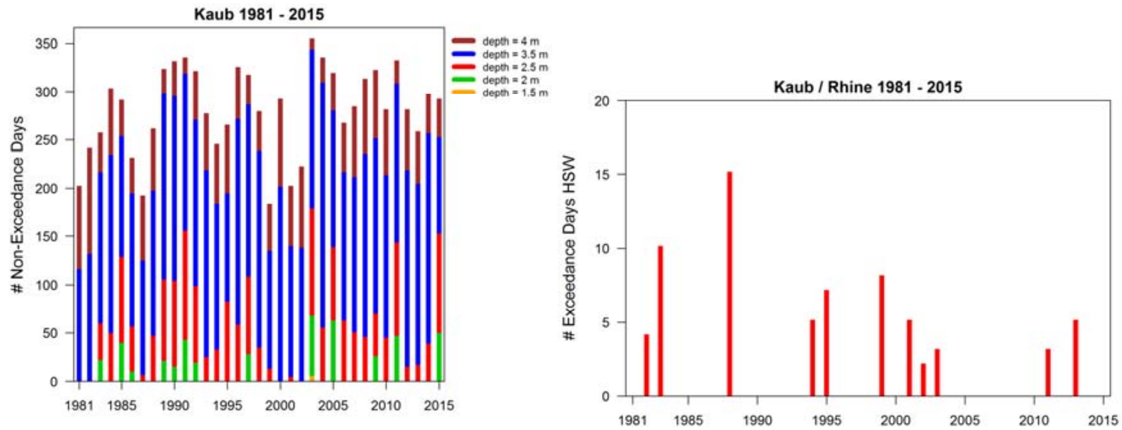

Figure 12: Non-exceedance days per year of selected water-depths (left part) and annual days exceeding the HSW-threshold (right part) at gauge Kaub / Rhine (period: 1981 – 2015)

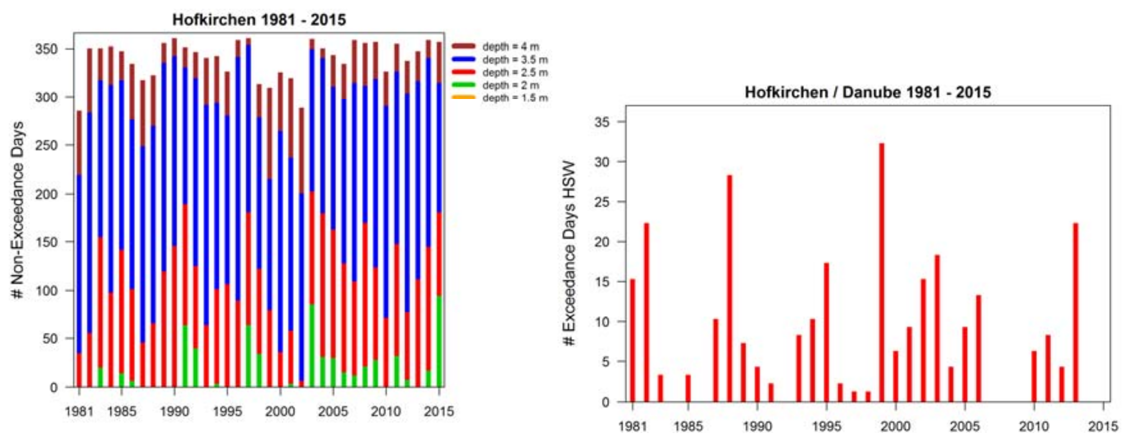

Figure 13: Non-exceedance days per year of selected water-depths (left part) and annual days exceeding the HSW-threshold (right part) at gauge Hofkirchen / Danube (period: 1981 – 2015)

Looking at the floods the differences between the waterways are less pronounced. The HSW-value at the Danube / gauge Hofkirchen is exceeded most frequently compared to Kaub / Rhine and Magdeburg / Elbe, but the duration of the single interruptions are comparable to those of the River Rhine (generally some days). At the Elbe the overall exceedance of the HSW-value isn't remarkable, but typically single flood events last for at least one week. So, navigation is interrupted less often than at Rhine or Danube, but in case of a flood the suspension of navigation normally persists over a longer period.

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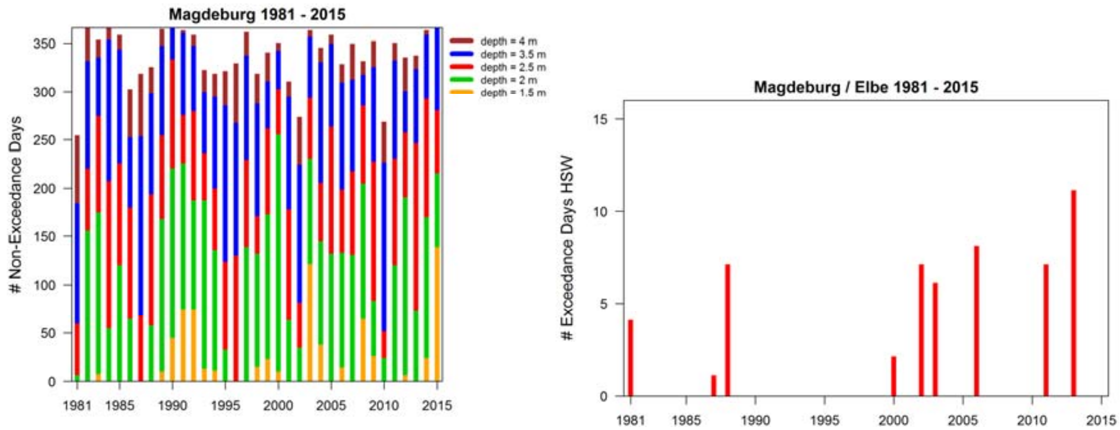

Figure 14: Non-exceedance days per year of selected water-depths (left part) and annual days exceeding the HSW-threshold (right part) at gauge Magdeburg / Elbe (period: 1981 – 2015)

Figure 15, Figure 16 and Figure 17, link the information on the above-discussed waterway-depth for representing gauges of Rhine, Danube and Elbe with the load of typical vessel types. In order to allow for a comparison between the different waterways the selected vessel types are the same for the three waterways, although the real fleet structure differs due to different navigation conditions. Table 5 contains a list of those vessel types considered and their relevant dimensions (Fläming & Schulte 2011, Zigic et al. 2012).

The parameter of interest to describe the navigation conditions is the so-called load factor indicating to which percentage the different ship types could have been load (quarter-wise average) in the period 2001 to 2015. The load-factor is calculated as the ratio of the current load (determined by the available water-depths) and the maximum load a specific ship is able to carry. For all ship types for squat and under keel clearance a sum of 0.30 m was assumed (added to the draught mentioned in Table 5). The current load is estimated by linear interpolation of the payload at minimum draught at the one at maximum draught. The load factor *LF* is calculated on a daily basis following this equation:

$$LF = \begin{cases} 0 & ; d < T_{\min} + 30 \\ \left(\dfrac{d - 30 - T_{\min}}{T_{\max} - T_{\min}} \left(P_{\max} - P_{\min} \right) + P_{\min} \right) / P_{\max} & ; T_{\min} + 30 \leq d < T_{\max} + 30 \\ 1 & ; d \geq T_{\max} + 30 \end{cases} , \qquad (1)$$

with d available fairway depth [cm], minimum / maximum draught T_{min}, T_{max} [cm], minimum / maximum payload P_{min}, P_{max} [t] and aggregated quarterly: January-March, April-June, July-September, October-December.

Table 5: Reference ship types used for load factor estimation, maximum, minimum draught Tmax, Tmin, maximum and minimum payload (Fläming & Schulte 2011, Zigic et al. 2012)

Name	Abbr	Length L [m]	Width B [m]	Draught Tmax [m]	Draught Tmin [m]	Payload Pmax [t]	Payload Pmin [t]
Gustav Koenigs-type(extended version)	GKext	80	8.2	2.5	1.1	1100	250
Johann Welker-type (extended version or Europe-type)	JW	85	9.5	2.6	1.2	1400	300
Large cargo vessel (GMS-type , 110 m)	GMS110	110	11.45	3.5	1.35	2900	400
Large cargo vessel (GMS-type , 135 m)	GMS135	135	11.45	3.5	1.35	3800	670
JOWI-type (containership)	JOWI	135	16.8	3.5	1.6	5200	1300
Coupled convoy Rhine (consisting of GMS-110 + 1 E II-barge)	CC-GMS110	186.5	11.45	3.5	1.35	5200	1000
Pushed convoy Rhine (consisting of push boat + 2 x 2 E II-barges)	PB_2x2EII	153	19	4	1.75	11000	3600
Large cargo vessel (GMS-95 type,"Stein"-class)	Stein	95	11.4	2.7	1.35	1910	265
Coupled convoy Danube (consisting of GMS-95 + 1 DE II-barge)	CC-GMS95	171.5	11.4	2.5	1.35	3200	930
Pushed convoy Danube (consisting of push boat + 2 x 2 DE II-barges)	PB_2x2DEII	153	22	4	1.6	6200	3450
Pushed convoy Elbe (consisting of push boat + TC100 + SP36/9.5 m barges)	PB_TC100_SP36	129	9.5	2.1	1	1800	540

Again the natural variations of the navigation conditions could be seen. The Rhine (Figure 15) offers the best conditions although the significant low flow periods (2003, 2005, 2011, 2015) could be identified by looking at the comparably low load factors for all vessel types, but of course most pronounced for the large-size vessels, like the pushed convoy (max. payload 11.000 tons). The difference of navigation conditions between Lower Rhine (gauge Ruhrort) and the Middle Rhine (gauge Kaub) are visible, e.g. at the Lower Rhine with a minimum load factor of about 0.6 for a large-size vessel (pushed convoy) or about 0.9 for the small vessels (Gustav Koenigs-type) appear.

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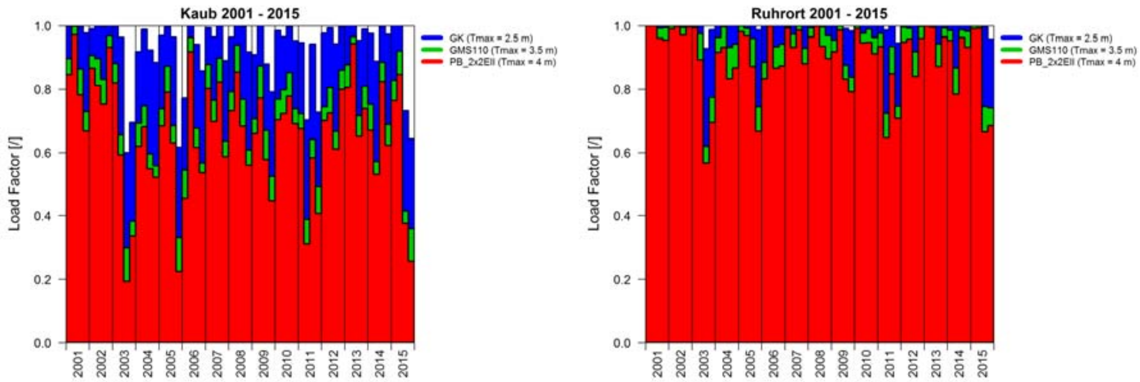

Figure 15: Load factor of selected vessel types at the waterway Rhine represented by gauge Kaub (left) and Ruhrort (right) for each quarter of the years between 2001 and 2015

At the Danube (Figure 16) the navigation conditions differ between the two gauges selected. The gauge Kienstock situated more downstream compared to Hofkirchen offers improved navigations conditions. Although the overall navigation conditions at the River Rhine seem to be slightly better than at the Danube, the load factors at the Danube are still high, with 0.87 / 0.98 (Gustav Koenigs-type), 0.61 / 0.84 (Large cargo vessel GMS 110) and 0.57 / 0.78 (pushed convoy Rhine) on average. Looking at the most significant low flow events 2003 and 2015 the gauges on Rhine and Danube show comparable load factors.

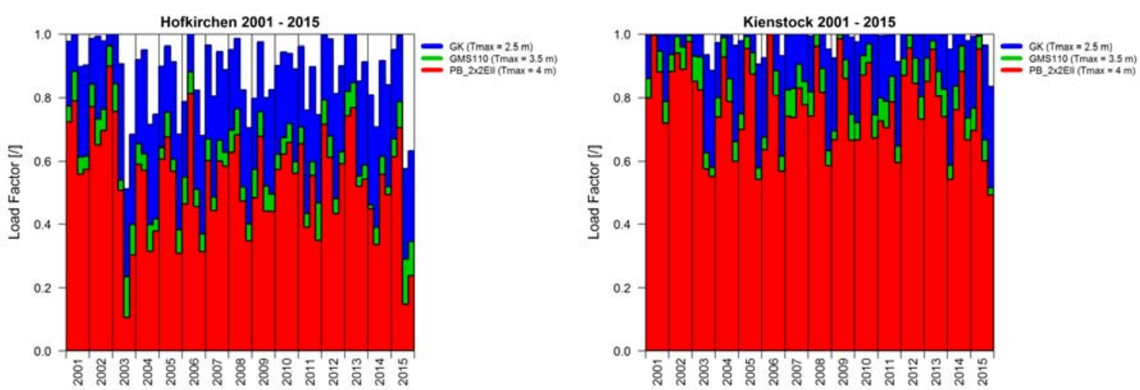

Figure 16: Load factor of selected vessel types at the waterway Danube represented by gauge Hofkirchen (left) and Kienstock (right) for each quarter of the years between 2001 and 2015

At the River Elbe (Figure 17) the navigation conditions are more or less the same when comparing the values for Dresden and Magdeburg. Periods where the large-size vessels sailing along Rhine and Danube could be operated efficiently would be rare, that is why the typical fleet structure along the Elbe differs from those at Danube or Rhine and primarily consists of smaller vessels or special vessels with a smaller draught respectively. One example for the latter case is the pushed convoy Elbe (see Table 5), which is able to carry up to 1800 tons with a maximum draught of 2.10 metres (e.g. the Johan Welker-types is able to carry up to 1400 tons but with a draught of 2.6 metres).

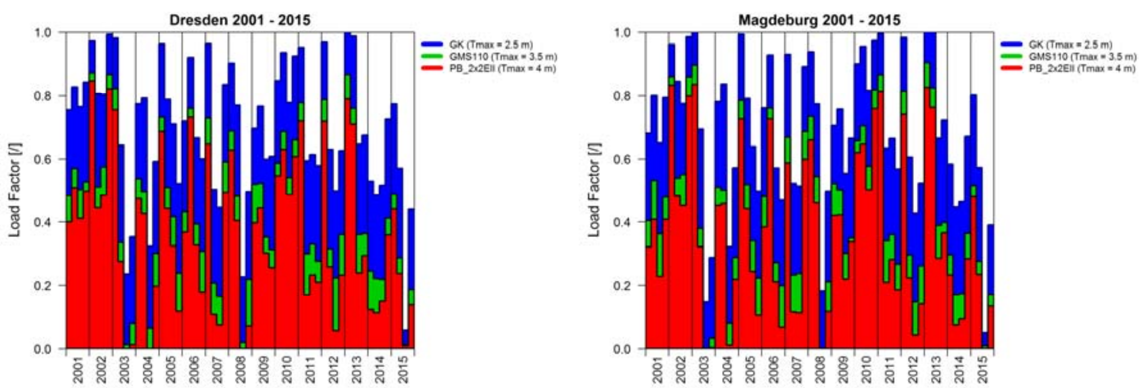

Figure 17: Load factor of selected vessel types at the waterway Elbe represented by gauge Dresden (left) and Magdeburg (right) for each quarter of the years between 2001 and 2015

While in the figures shown above the vessel types, for which the load factors are presented, are the same for all waterways, Table 6 shows the results for all vessel types typically sailing on Rhine, Danube, and Elbe. The load factors of those vessel types predominantly used on the specific waterway are highlighted with a grey box.

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Table 6: Mean load factor of reference ship types of the period (2001-2015)

Ship	Tmax	Kaub	Ruhrort	Dresden	Magdeburg	Hofkirchen	Kienstock	Wildungsmauer
GK	2.5	0.93	1	0.7	0.69	0.87	0.98	0.84
JW	2.6	0.91	0.99	0.65	0.65	0.84	0.97	0.81
GMS110	3.5	0.73	0.94	0.45	0.45	0.61	0.84	0.62
GMS135	3.5	0.74	0.95	0.47	0.47	0.62	0.84	0.64
JOWI	3.5	0.73	0.94	0.46	0.46	0.61	0.84	0.63
CC-GMS110	3.5	0.74	0.95	0.48	0.48	0.63	0.85	0.64
PB_2x2EII	4.0	0.68	0.9	0.45	0.45	0.57	0.78	0.59
Stein	2.7	0.87	0.99	0.56	0.55	0.78	0.96	0.76
CC-GMS95	2.5	0.92	1	0.66	0.66	0.86	0.98	0.83
PB_2x2DEII	4.0	0.80	0.94	0.66	0.66	0.73	0.86	0.74
PB_TC100_SP36	2.1	0.97	1	0.82	0.81	0.95	1	0.92

Table 6 gives an overview of the mean load factors (averaged over the period 2001 – 2015) for vessel types typically sailing along the waterways Rhine, Danube and Elbe. In addition to the gauges already presented above the table contains results for gauge Wildungsmauer / Danube as another important bottleneck of this waterway, too. Again the differences between the waterways become visible. The Lower Rhine, reference gauge Ruhrort, offers the best navigation conditions of all gauges shown here, allowing also large-sized inland waterway vessel to reach the port of Duisburg, being the world's largest inland port.

As already shown in chapter 4 the overall transport volume is significantly lower at the inland waterway Elbe as it is at the Danube or the Rhine. The average load factors reflect this fact with comparatively low values of 0.66 (Johann Welker-type extended) and 0.70 (Gustav Koenigs-type).

5 Vulnerability of inland waterway transport and waterway management to hydro-meteorological impacts

Main findings:

- The main vulnerability of IWT with regard to hydrological impacts results from the close correlation of the operation efficiency and the available water-depths, which is highly variable along the waterways (except canals, impounded rivers). The intensity and duration of low flow periods (as floods are comparatively short events) generally determine the intensity of interference and vulnerability of IWT.
- Water-depth affects the maximum amount of cargo, the possible vessel speed and its fuel consumption (low water depths reduce load capacity and vessel speed while fuel consumption increases).
- Increasing transport costs and less available transport capacity have negative influence on the companies offering / handling the transport (the "carrier") as well as on the costumers (the "consignor").
- The carriers are confronted with additional transport costs (only partly covered by low water surcharge) and the danger to lose customers permanent (as transport might be partly shifted to other transport modes).
- Industries relying on IWT face the problem to avoid reduction of the manufacturing processes due to insufficient raw material feed or spilling over of warehouses as well as to minimize transport costs at the same time.
- Hydrological forecast fitted to the requirements of the different waterway users (carrier as well as consignor) are an important measure to reduce IWT's vulnerability with regard to hydro-meteorological impacts.
- Given sufficient skill longer lead-times (in order to anticipate low flow periods in due time) and probabilistic forecast (in order to support risk-based decision making) are required to mitigate IWT's vulnerability sustainably.

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The key requirements of means of transportation are a high degree of reliability and availability. Although all means of transportation could be affected by hydro-meteorological extremes (e.g. roads or train lines might be inundated due to floods or blocked by landslides triggered by intense rainfall, heavy wind gusts could affect air traffic etc.) the vulnerability of IWT shows a particular close interaction to hydro-meteorological impacts, not solely on extremes. On the one hand the availability of waterways is influenced by hydro-meteorological effects, primarily floods and river ice leading from time to time to suspension of navigation (see chapter 6.1, 6.2and 6.3). High water-level thresholds causing a disruption of traffic are considerably lower (e.g. HSW definition in Austria 1% of days in a year exceeds HSW on average) and therefore occurring more often than those causing flooding of main roads or railway tracks (generally return periods > 50 years).

On the other hand, the main vulnerability of IWT with regard to hydrological impacts doesn't result from a limited availability but from the close correlation of the operation efficiency and the available water-depths along the waterways. IWT is highly dependent on the alternating water-levels. Therefore, in contrast to truck and railway, availability and efficiency of the transportation infrastructure is variable over time.

With the exception of canals and impounded river stretches the water-level and respectively the water-depth, determining the efficiency of the transportation infrastructure, vary along the waterways due to the hydro-meteorological conditions and its seasonal variations (see chapter6). That's the reason why e.g. the coordinator of EU-project WEATHER once stated with regard to hydrological impacts / climate change that "[...] the most vulnerable mode of transport appears to be inland navigation" (European Commission 2012). Table 7 summarizes the major impacts of hydro-meteorological extremes on IWT and waterway management (modified after Kreuz et al. 2012).

The water-level, even beyond floods leading to a suspension of navigation, affects the operation efficiency indirectly by the transport costs. The transport costs of an inland vessel are sensitive to the water-level, because the latter affects the water-depth, which again affects:

- the maximum amount of cargo,
- the speed and
- the fuel consumption.

The more cargo a vessel is carrying the higher its draught and therefore to avoid grounding a specific water-level offering the relevant depth is required (see Table 5). The water-level is primarily a load-limiting factor. But furthermore the water-level and respectively the water-depth have influence on the vessels fuel consumption and the speed, too. There is a physical dependence between the propulsion power required to reach a certain speed and the relation of water-depth and ship's draught. In general a vessel could drive faster with the same propulsion power in deep water than in shallow areas. This leads to a decrease in travel time (the goods arrive faster at their destination) and the fuel consumption is lower (due to a lower operation period of the engines). The so-called power-speed-profiles are definable for each specific vessel type characterized by its size, the hull shape and the propulsion unit (Bruinsma et al. 2012).

Increasing transport costs and less available transport capacity have negative influence on the companies offering / handling the transport (the "carrier") as well as on the costumers (the "consignor"), typically industries relying on water-bound transportation (generally mass-cargo affine industry like power plant, chemical industry etc.). The logistic companies aim to cover their extra expenses during low flows. Generally long-term contracts exist between the carrier and the consignor which assume regular water-level conditions as they could be expected e.g. due to climatology. In case of low flows those contracts normally arrange the payment of so-called "low water surcharge" in case of a low flow situation. The low water surcharge is an extra amount of money to be paid to the carrier in order to compensate the exponentially rise of costs during low flows (see Figure 2). The rate depends on the absolute water-level at representative gauges (e.g. gauge Kaub relevant for destinations south of Koblenz or gauge Ruhrort for destinations north of Koblenz up to Duisburg). Of course, due to this surcharge IWT (partly) loses its cost benefit compared to the competing modes of transportations, particularly railway. So it might happen that during low flow situations (or floods when waterways are closed) transport is partly shifted to the other modes, if they offer free capacities and if the transport is technically feasible. But it has to be mentioned, that the free capacity of road and railway are highly limited and that such shifts require additional time for preparation, so that forecasting becomes an important issue (chapter 8).

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Table 7: Major Impacts of hydrometeorological extremes on waterway management and inland waterway transport (modified after Kreuz et al. 2012)

Event Type	Impacts	Consequences to infrastructure	Consequences to operations/services	Affected Waterway type / Region
Flood	high water-levels high flow velocities changes in sediment transport occurrence of driftwood, local aggradation, degradation and scour	Modification of river and bank morphology Damage to as well as clogging or sedimentation of navigation signs, gauges, ramps and stairs, berths, banks, tow paths, port and lock areas, dams, groins and training walls Flooding of protected areas	Suspension of navigation Delays Vessel damage (e.g. propulsion devices by driftwood)	Impounded and free-flowing waterways / all
Low Flow Events	low water-levels low flow velocities	Changes in sedimentation and aggradation processes in comparison with normal or high water conditions Insufficient navigation conditions deviating from internationally agreed ones	Reduced cargo carrying capacity of vessels Increased power demand due to shallow water resistance and increased sailing times Delays due to shallow water resistance Possibly interruption of navigation Increased probability of grounding of vessels	Free-flowing waterway, especially bottlenecks / all
Ice	Locally appearance of ice and ice jams, freezing of locks and mooring devices	Possible damage to navigation signs and infrastructure Prevented lock operation Need for ice breaker assistance on selected waterways, in hydropower plant and port areas	Suspension of navigation Navigation at own risk due to missing navigation signs damaged by ice Delays	Canals / all Impounded Waterways / all Free-Flowing waterways / Elbe, Middle Danube (Continental Climate)
Wind	Increased side forces on vessels and cargo on deck increased heel and rolling, reduced manoeuvrability	Possible material damage due to collisions	Possible sliding of empty unlashed containers on deck and loss of cargo Suspension or interruption of navigation Flooding of cargo holds and loss of stability, capsize Accidents with material damage Increased time for manoeuvring operations Delays	All
Reduced Visibility	Reduced speed, interruption of navigation of vessels without radar		Delays	All

The intensity and duration of low flow periods (as floods are comparatively short events, normally of some days – see chapter 6.2) generally determine the intensity of interference and vulnerability of IWT. The success criteria of the shipping companies are primarily the satisfaction of customer needs. These are the provision of the desired loading space and also the timely delivery of the transported goods. Thus the ultimate success criterion is profit maximization (Jonkeren et al. 2007, Bruinsma et al. 2012, Nilson et al. 2012).

Industry is dependent on reliable and continuous transport, especially as there is a clear tendency to produce "just-in-time", which leads to a reduced storage capacity for raw material as well as for products. Based on a study by (Scholten 2010) most of the industries in the Rhine area are (just) able to produce 7 up to a maximum of 14 days without transport. Longer periods of low water constitute an interference which might even lead to a shutdown of production with the corresponding economical losses. Figure 18 depicts the mechanism of IWT's vulnerability in a schematic and simplified way, with decreasing water-levels as the most relevant hydrological trigger. The two perspectives (on the one hand the carrier and on the other hand the consignor) are symbolised via different colours, which of course are partly overlapping.

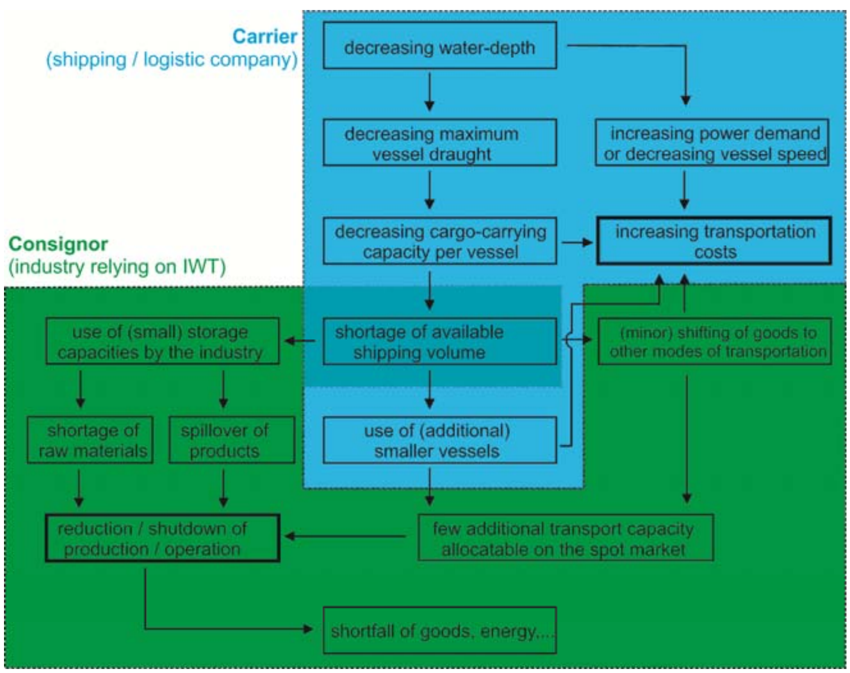

Figure 18: Schematic representation of the functional chain of the vulnerability of IWT due to low flows / droughts (modified after Scholten 2010)

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Hydrological forecast fitted to the requirements of the different waterway users (carrier as well as consignor) are one promising measure to reduce IWT's vulnerability with regard to hydro-meteorological impacts (see also chapter 8.2).Ice forecasts and early warning systems are required for the canals and impounded stretches to reduce the vulnerability against river ice, low flow forecasts are mainly required for the bottlenecks of the waterways to reduce vulnerability against low flow situations, high flow forecasts are required for all parts of the impounded and free-flowing waterways to be prepared for limitations and blocking of the waterways.

As especially low flow situations are long-lasting events an important aspect to reduce the vulnerability of IWT is a sufficient long lead-time of the forecast, given that it has sufficient skill to support decisions. Additional lead-times are particularly needed in order to strengthen the inclusion of waterway transport within multi-modal transport chains as well as to optimize waterway management overall.

Probabilistic forecasts are important to quantify and communicate the forecast uncertainties to the end-user. Rational decision making based on a cost-benefit analysis is only possible if the full predictive uncertainty distribution of the variable of interest is known.

Of course, hydrological forecasts, even with extended lead times won't be able to avoid hydro-meteorological interferences, but it is realistic that improved forecasts offer the possibility e.g. to optimize the fleet structure related to upcoming waterway conditions or to adapt of the stock management of enterprises (see Figure 18) to a certain degree.

6 Hydro-meteorological extremes

Main findings

- Low flows are slow processes dependent on various climatic factors, mainly precipitation deficit over a large area during the last months, often combined with high evaporation losses and catchment conditions. For large catchments the preceding winter or even preceding years can be important.
- Extreme low flow events with significant impact on IWT occurred in 2003 and 2015 (for all catchments of the study area).
- The mechanisms of flood generation are quite heterogeneous in large river basins. To cause a major flood, the interaction of a triggering hydro-meteorological event and corresponding initial hydrological conditions of the basin is required. Furthermore the intensity and characteristic of flood events are determined by the interaction of the major tributaries with the main river (the absolute amount of water entering the main river and the temporal interaction of the different tributaries).
- Floods relevant to IWT differ between the waterways, important events are 1999, 2003, 2011, 2013 (Rhine), 2002, 2005, 2006, 2013 (Danube) and 2002, 2006, 2011, 2013 (Elbe)
- River ice is caused by continuously low air temperatures over several days in combination with low flow velocities. That's why canals and impounded rivers are affected in particular by river ice. Artificial influencing factors are the heat and salt inflows from power plants and industry.

Due to the different types of extremes limiting IWT it is not possible to define one single meteorological criterion defining extremes. If a meteorological event is becoming critical depends on the intensity, duration, spatial distribution of precipitation, temperature conditions (evaporation, accumulation / melting snow), the initial conditions of the catchment (e.g. soil moisture, snow storage,...) and the time of year as the flow regime of the waterways are seasonally and locally varying.

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6.1 Low flow events

Low flow events or hydrological droughts are seasonal phenomena as they generally occur after periods of low rainfall and high evapotranspiration due to high temperatures in rainfall dominated flow regimes ("summer low flows") or when precipitation is stored as snow in snow-dominated runoff regimes ("winter low flows"). Both phenomena lead to a decrease of water stored in the soil and aquifers and a decrease in the flow of rivers (WMO 2008). They generally occur in the months with the lowest mean monthly flows (see Figure 4). In the study area either situations or a combination of both phenomena can occur.

The evolution of extreme low flows / hydrological droughts in summer time is a slow process dependent on various climatic factors such as precipitation deficit over a large area during the last months, often combined with high evaporation losses and catchment conditions. For large catchments with large storages and therefore a long-lasting memory, the preceding winter or even preceding years can be important (Tallaksen et al. 2009). As extreme meteorological droughts are large scale events in space and time the extreme low flow events such as 2003 and 2015 occurred in all catchments of the study area in the same period.

Two low flow indicators are used here to describe the low flow events in the study area:

- Annual lowest seven-day mean flow NM7Q to get an impression of the extremeness / magnitude of the low flow event. The daily flow record for the gauges was analysed for the lowest moving average flow over 7 consecutive days in each year, to avoid a split of low flow events at the turn of the year, the water year from 1 April to 31 March is used for analysis (WMO 2008).
- The annual number of days below defined quantiles of the flow duration curve of the reference period 1981-2010 to get an impression of the duration of the low flow events. As quantiles the 95%- (similar to the definition of GlW and LNWL), the 90%- and 75%-quantiles (Q_FDC95, Q_FDC90, Q_FDC75) are used here, because for navigation also low flow events with lower magnitudes, leading to a reduction of load, are of importance.

To visualize the seasonality of low flows of the considered waterways the occurrence dates (first day) of the annual NM7Q low flow events are displayed on a unit circle representing the annual cycle in Figure 19 (Burn 1997). The seasonality vector after Burn (1997) points to the mean date of occurrence of the low flow events and the spread of the occurrence dates is represented by the length of the vector (length 1, outer circle in Figure 19: no spread of the occurrence dates indicating strong seasonality, length 0: large spread of the occurrence dates indicating no seasonality of the events).

In snow dominated flow regimes (e.g. Kienstock, Nagymaros and Maxau) the mean date of occurrence is the end of year when snow melt from Alpine areas is not present anymore and precipitation is stored as snow in the Alpine areas. In rainfall dominated flow regimes (e.g. Dresden and Mageburg) the mean date of occurrence is late summer due to the high evapotranspiration values in summer time. In mixed flow regimes (e.g. Hofkirchen, Kaub) the minimum flows are earlier in time than in snow-dominated flow regimes but later than in rainfall dominated flow regimes because of the higher summer flows from the snow-melt of the alpine areas of the catchments.

At the River Rhine the seasonality vector (blue colours) shifts from End of November to the first half of October in the flow direction of the River Rhine as the pluvial influence increases during the course of the river. At the River Elbe the seasonality vectors are all located in August. At the River Danube the seasonality vector jumps from first half of October (Hofkirchen) to the mid of December (Kienstock) due to confluence of the Danube with the glacial-nival dominated Inn tributary between the two gauges. The pluvial dominated tributaries between Kienstock and Nagymaros lead to a back-shift of the seasonality vector by a month towards the second half of November.

Extraordinary extreme low flow events in terms of magnitude and duration of the last 15 years have been: 2003, 2005, 2008, 2011, and 2015. Figure 20 shows the hydrographs of these low flow years for selected gauges in the study area. As for navigation not only the magnitude of the low flow event is of importance Figure 21 shows the annual non-exceedance days of the 95% (Q_FDC95), 90% (Q_FDC90), 75% (Q_FDC75) of the flow duration curve of the period 1981-2010. The figures makes clearly visible that besides the 1991 event the 2003 and the 2015 low flow events were for all considered waterways extreme in terms of magnitude and duration.

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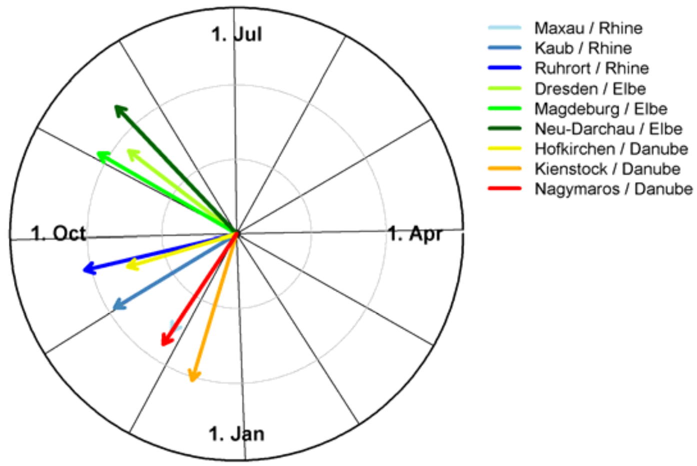

Figure 19 Seasonality vector after Burn (1997) of the occurrence dates of the Annual lowest seven-day mean flow NM7Q on the unit circle for the period 1981-2015 for gauges at the waterways Rhine, Elbe, and Danube. Length of vector represents the spread of the occurrence dates (length 1, outer circle: no spread of the occurrence dates indicating strong seasonality, length 0: large spread of the occurrence dates indicating no seasonality of the events)

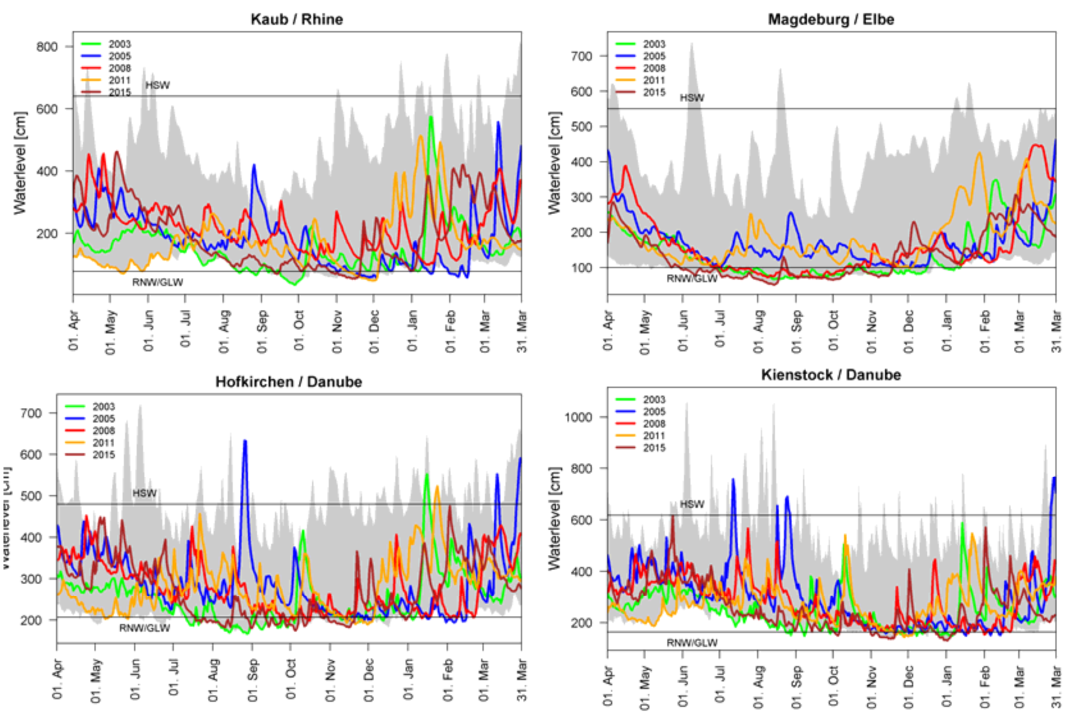

Figure 20: Extreme low flow years at the gauges Kaub / Rhine, Magdeburg / Elbe, Hofkirchen / Danube and Kienstock Danube. Grey band shows the climatology of the observed daily mean flows of the period 1981-2015.

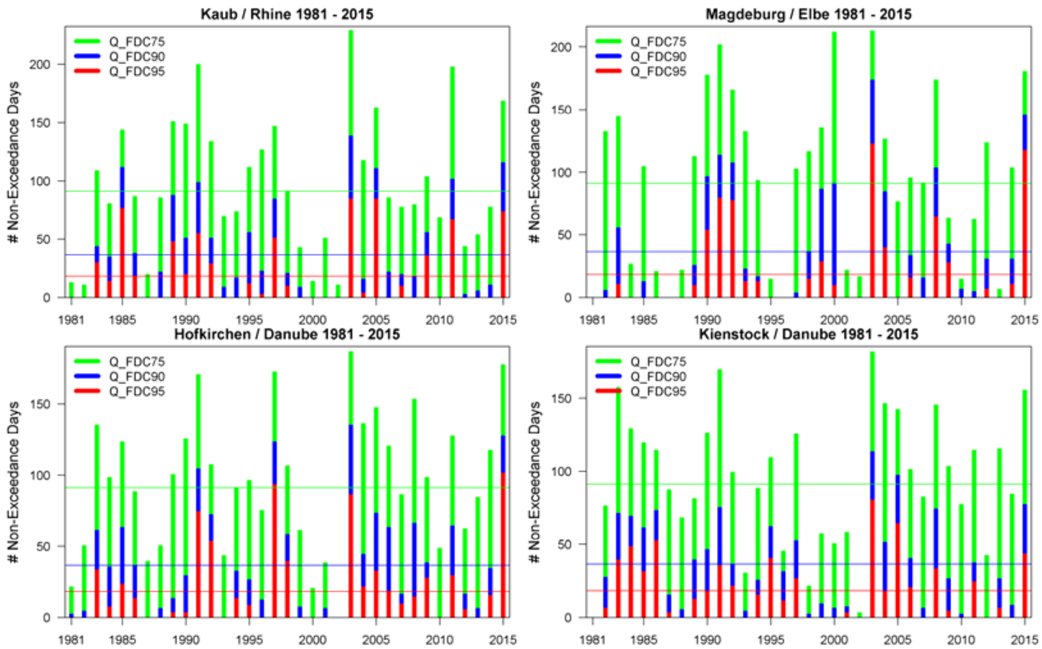

Figure 21: Number of days per year below selected quantiles 95% (Q_FDC95), 90% (Q_FDC90), 75% (Q_FDC75) of the flow duration curve of the period 1981-2010 at the gauges Kaub / Rhine, Magdeburg / Elbe, Hofkirchen / Danube and Kienstock Danube.

Figure 22, Figure 23, and Figure 24 shows annual NM7Q, the mean monthly flows and the corresponding mean monthly flow anomalies (anomaly meant as deviation of a specific value from the long-term mean) as for selected gauges in the Rhine, Danube and Elbe basin as well as the main hydro-meteorological drivers for extreme low flow events: accumulated precipitation deficit over the last 6 months, to describe the meteorological conditions of the months preciding the low flow event, accumulated precipitation deficit over the last 12 months, to cover low flow phenomena which are depended on a precipitation deficit of a longer time scale, and the cumulated potential evapotransporation of the last 12 months. To illustrate the combined effect of precipitation and evapotranspiration the cumulated climatic water balance of the last 6 months is shown too. Climatic water balance is defined as the residuum from precipitation and potential evaporation. Positive values of the climatic water balance means that more water is supplied as needed (storages in the catchment are filled by the surplus), negative values indicate consumption of the available soil moisture by evapotranspiration.

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As hydrological droughts are large scale phenomena the hydro-meteorological drivers are aggregated for large regions of the considered basins shown in Figure 3. Precipitation deficits are derived from the EOBS dataset (Haylock et al. 2008), potential evapotranspiration is derived from temperature of the EOBS dataset and global radiation of the ERA-Interim dataset (Dee et al. 2011) using the approach of Turc-Wendling (Wendling et al. 1991). The deficits and flow anomalys are calculated for each month separately using the long-term monthly means of the period 1981-2010 as reference.

As expected, the cumulated climatic water balance shows a pronounced seasonality with minimum values in late summer. The date of occurrence of the low flow events at the waterway Elbe and River Rhine and gauge Hofkirchen at the Danube nicely fits with the time of the minimum values. The date of occurrence at gauge Kienstock is delayed to the maximum value because of the different flow regime with low flows generally occurring in autumn.

The low flow event 2003 followed a wet period with a flood in January 2003 on the considered waterways (BfG 2006). It occurred from a large precipitation deficit in the period March to September and the hot European summer of 2003 characterized by extreme temperatures for the months June-August which were 5°C warmer than the 1961-90 average (Fink et al. 2004) and therefore high evapotranspiration values which are clearly present in all catchments in Figure 22, Figure 23, and Figure 24. At the waterway Rhine minimal water-levels were observed at the end of September 2003. At the upper Danube gauge Hofkirchen the minimal water-levels were observed at the end of August. At gauges Kienstock and Nagymaros the low flow event lasted up to the end of 2003. At the waterway Elbe extreme water-levels were observed at the end of August but as in the case of the gauges Kienstock and Nagymaros the event lasted up to the end of the year 2003.

The recent drought in Europe in 2015 was one of the most severe droughts since 2003 with low flow values over a long period starting in June up to the end of November at the waterway Elbe and starting in August up to the end of the year 2015 at the waterway Rhine and Danube. The summer was characterized by exceptionally high temperatures with corresponding high evapotranspiration values (Figure 22, Figure 23, and Figure 24) in many parts of central and eastern Europe, with daily maximum temperatures 2 °C warmer than the seasonal mean (1971-2000) over most of western Europe, and more than 3 °C warmer in the east (Ionita et al. 2016, Laaha et al. 2016). It was also characterised by a lack of rainfall summing up during the event (Figure 22, Figure 23, and Figure 24).

To summarize it could be stated that for the considered catchments the following hydro-meteorological conditions lead to extreme low flow events:

- Precipitation deficit over a large period > 6 months
- High temperatures over a long period leading to high evapotranspiration values
- As extreme low flow events in summer are combined effects of precipitation and high temperatures leading to high evapotranspiration values, the climatic water balance is an important indicator for low flow events. Large negative values over a long time indicate consumption of the available soil moisture by evapotranspiration.

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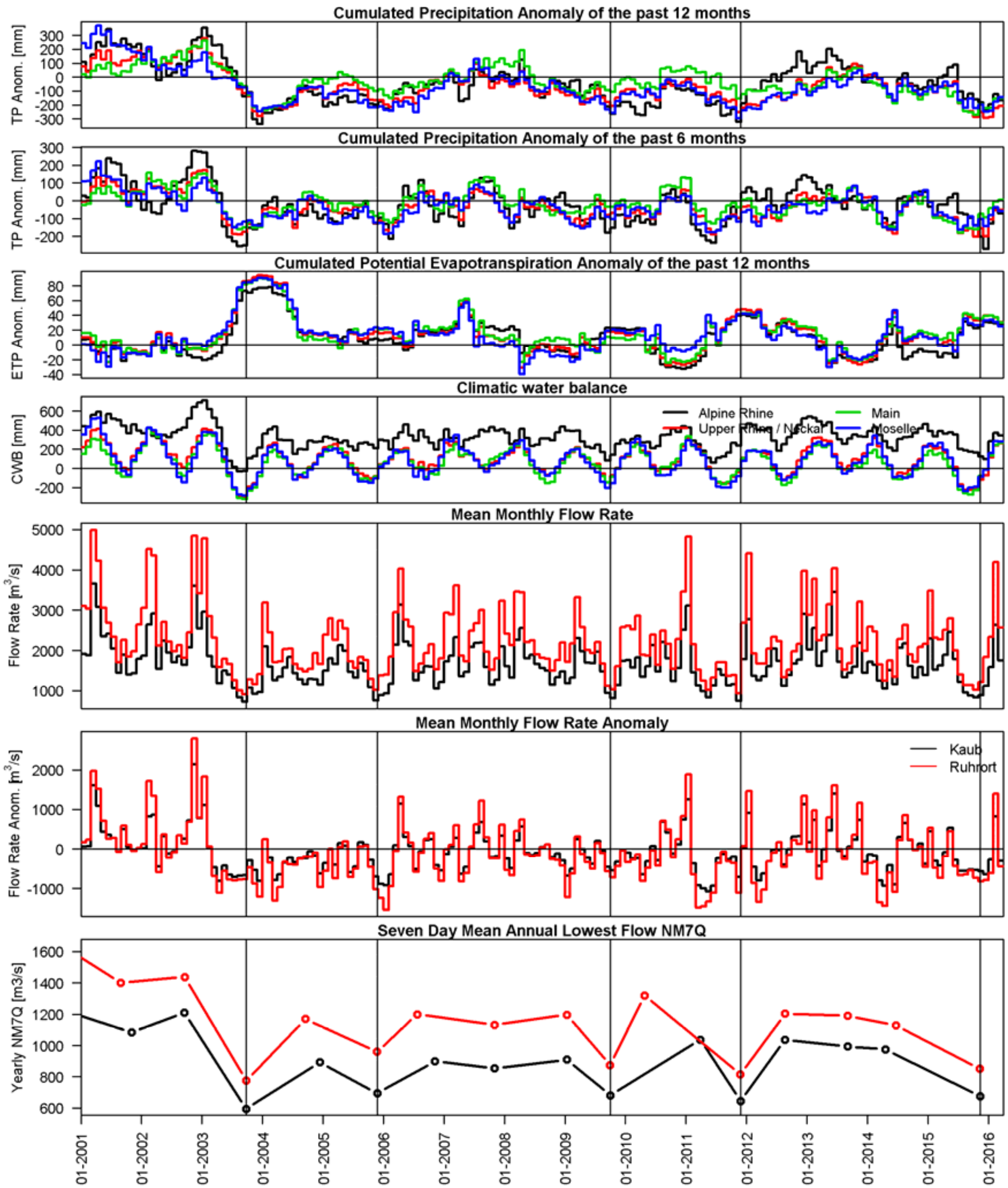

Figure 22: Annual lowest seven-day mean flow NM7Q of the period 2001-2015, mean monthly flow rate and mean monthly flow rate anomalies at selected gauges in the Rhine basin, cumulated precipitation deficit of the last 6 and 12 months, cumulated potential evapotranspiration of the last 12 months, cumulated climatic water balance of the last 6 months of defined hydro-climatic regions in the Rhine basin (see Figure 3). Marked are the five lowest NM7Q events at gauge Kaub.

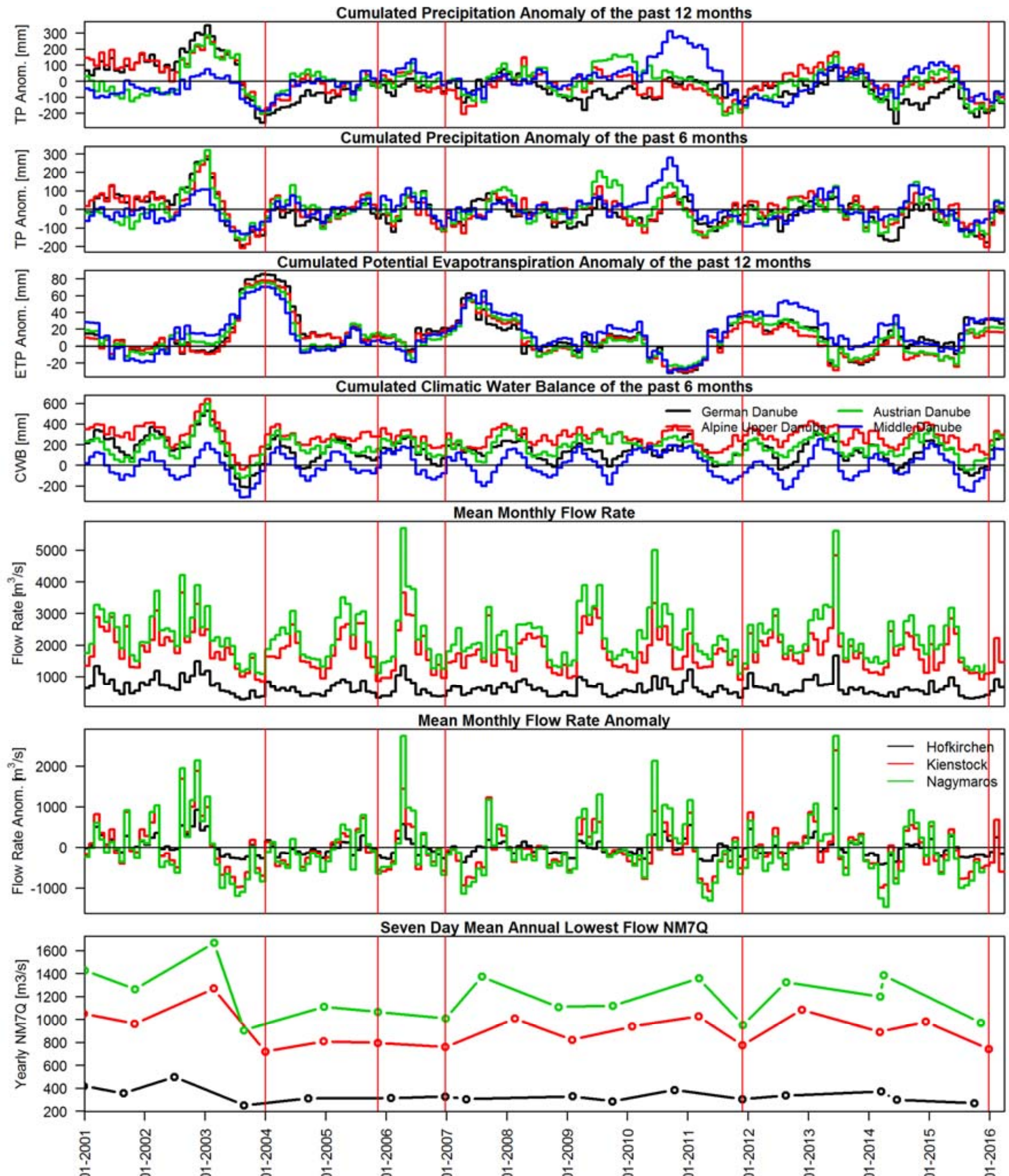

Figure 23: Annual lowest seven-day mean flow NM7Q of the period 2001-2015, mean monthly flow rate and mean monthly flow rate anomalies at selected gauges in the Danube basin, cumulated precipitation deficit of the last 6 and 12 months, cumulated potential evapotranspiration of the last 12 months, cumulated climatic water balance of the last 6 months of defined hydro-climatic regions in the Danube basin (see Figure 3). Marked are the five lowest NM7Q events at gauge Kienstock.

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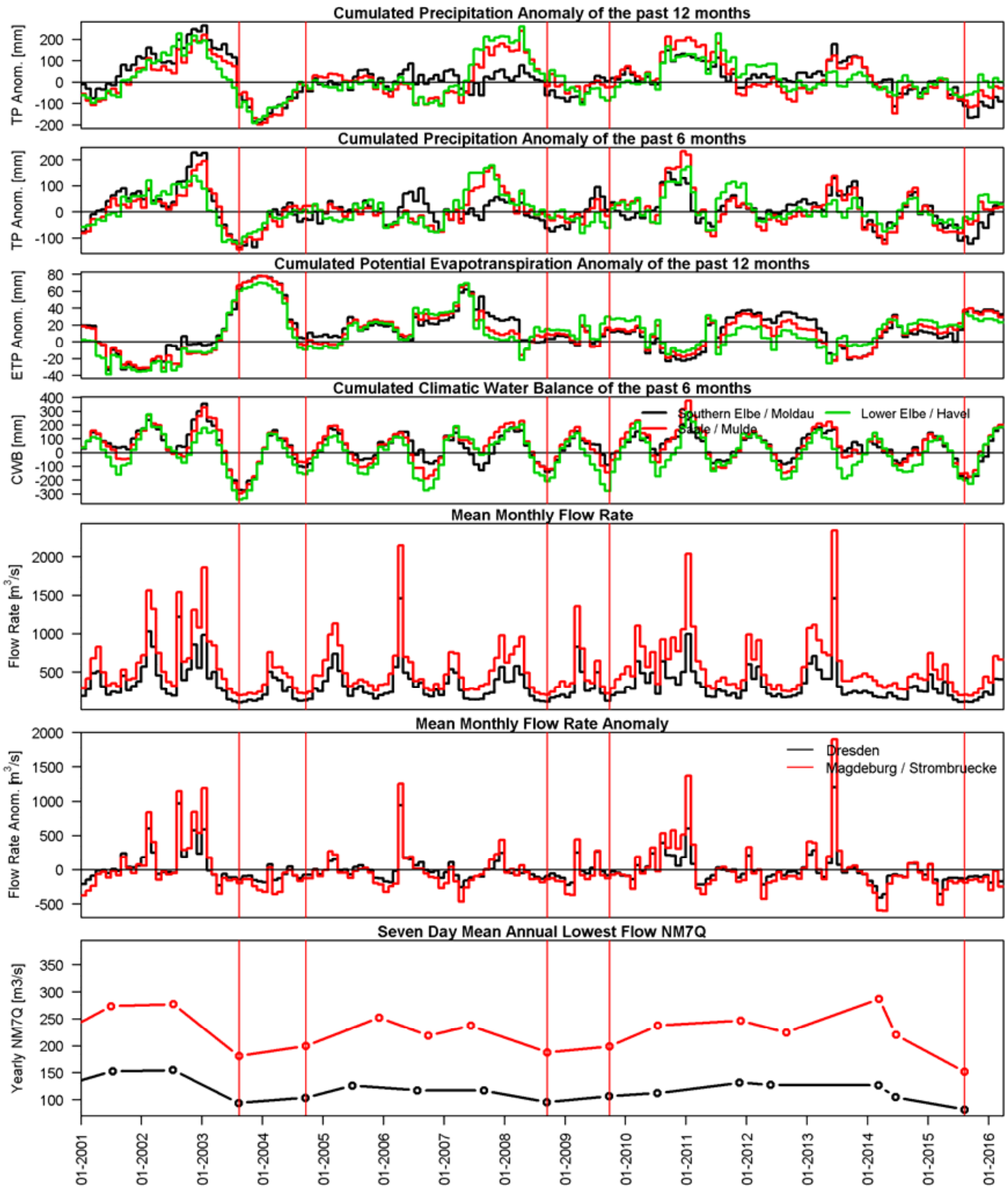

Figure 24: Annual lowest seven-day mean flow NM7Q of the period 2001-2015, mean monthly flow rate and mean monthly flow rate anomalies at selected gauges in the Elbe basin, cumulated precipitation deficit of the last 6 and 12 months, cumulated potential evapotranspiration of the last 12 months, cumulated climatic water balance of the last 6 months of defined hydro-climatic regions in the Elbe basin (see Figure 3). Marked are the five lowest NM7Q events at gauge Magdeburg.

6.2 Floods

The main driver for flood situations in rivers used as inland waterways, which drain relatively large river basins, is large-scale precipitation lasting several days, which is sometimes intensified by snow melt. Solely snow driven spring floods (triggered my melting processes due to rapid temperature rise) without significant precipitation input typically don't lead to floods relevant for transportation in the Central European waterways. Also small-scale and / or short-term (intensive) rainfall events, causing severe (flash) floods in smaller rivers, normally don't affect the larger rivers, like the Rhine, significantly. To cause a major flood in a large river basin, the interaction of a triggering hydro-meteorological event (usually intensive rainfall) and corresponding initial hydrological conditions of the basin (e.g. a high soil moisture content due to prolonged wet conditions, big snow pack due to a snowy winter season or a largely sealed surface due to intensive frost the previous days) is required. Furthermore the intensity and characteristic of flood events in large rivers are determined by the interaction of the major tributaries with the main river (e.g. Aare, Main and Moselle for Rhine or Isar, Inn and Enns for the Danube). Beside the absolute amount of water entering the main river the temporal interaction of the different tributaries is a very important aspect. In case of superposing flood waves from the different parts of a catchment, the flood peaks in the main river could be increased significantly.

The aforementioned facts show that the mechanisms of floods generation are quite heterogeneous, making it difficult to identify hydro-meteorological criteria leading to (extreme) floods clearly. Although the initial conditions of the specific river basin, which is the result of the hydro-meteorological situation of several previous weeks, are an important criterion to identify critical situations possibly leading to floods, critical climate conditions for floods are more short-term and not homogenous for a large area like Central Europe when compared to low flow events (see chapter 6.1). Figure 25 displays the annual maximum daily flows for the waterways Rhine (at the top), Elbe (in the middle) and Danube (at the bottom) each represented by three gauges at different locations along the rivers for the period 1981 to 2015. To avoid a split of high flow events at the turn of the year, the water year from 1 November to 31 October is used for analysis. It could be seen that in most cases major floods don't occur in all of the three river basins at the same time and even within one basin a flood not necessarily take place in all parts of the rivers. For

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example the flood 2013 was an appreciable event in the Upper Rhine (gauge Maxau) and Middle Rhine (gauge Kaub), but not for the Lower Rhine (gauge Ruhrort). The colored columns in Figure 25 indicate the whether it was a winter (light blue) or a summer (white) flood event.

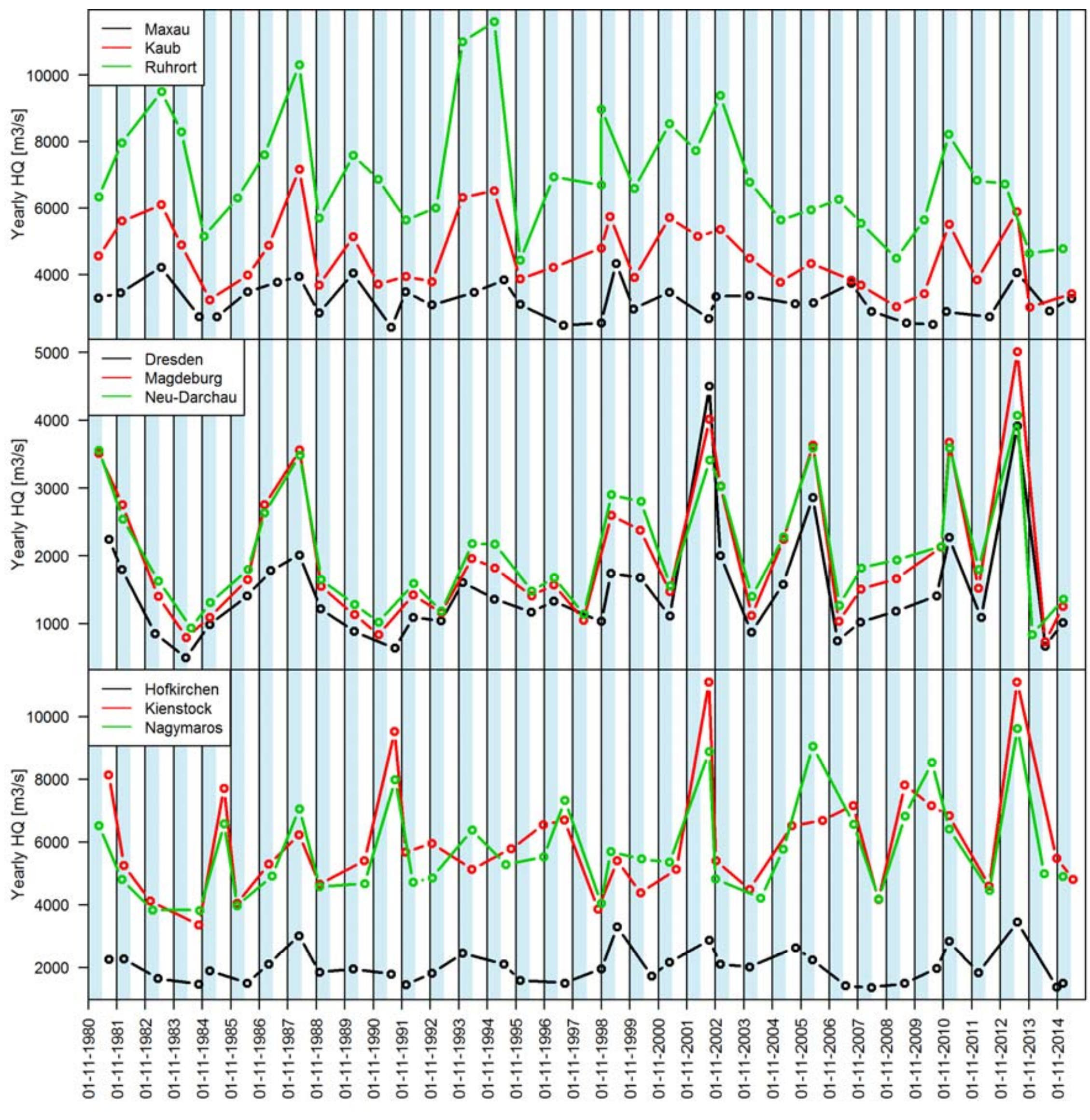

Figure 25: Annual maximum flows for the period 1981-2015 for gauges at the waterways Rhine, Elbe, and Danube

According to the low flows the seasonality of floods is characterized using the seasonality vector after Burn (explanation see chapter 6.1) based on the annual maximum discharge. A long vector indicates a small spread of the occurrence dates of the annual maximum flow, while a small vector length shows a large spread of the occurrence dates of floods indicating a low seasonality of the flood events.

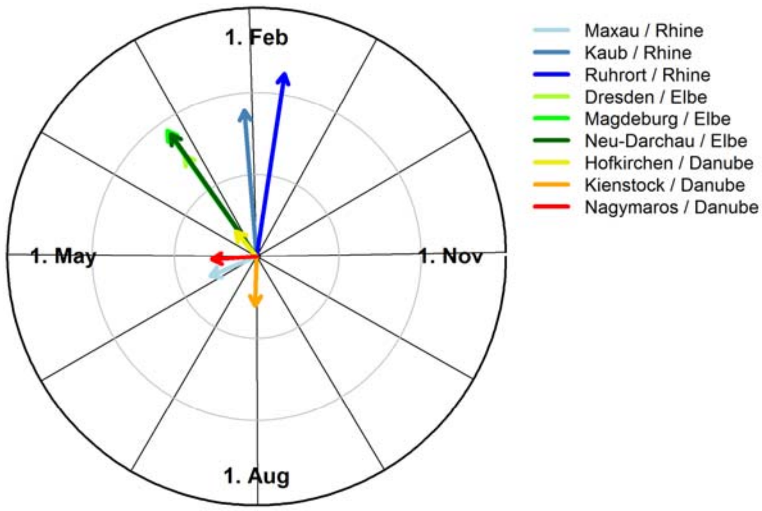

Figure 26: Seasonality vector after Burn (1997) of the occurrence dates of the annual highest flows on the unit circle for the period 1981-2015 for gauges at the waterways Rhine, Elbe, and Danube. Length of vector represents the spread of the occurrence dates (length 1, outer circle: no spread of the occurrence dates indicating strong seasonality, length 0: large spread of the occurrence dates indicating no seasonality of the events)

The Middle and Lower Rhine (gauge Kaub and Ruhrort) show a pronounced seasonality of floods with a clear tendency to winter flood events. In the upper part of the river Rhine (gauge Maxau) there is no such clear seasonal behaviour of the annual maxima in spite of the nival dominated flow regime. Typical winter events, like more downstream, could be observed, but also maximum discharges in late spring / early summer (e.g. like the 1999 floods) frequently occur. All the stations along the Danube also don't show a clear seasonality regarding the annual maximum flows. More rainfall driven events (occurring in autumn and summer) alternate with primarily snowmelt driven (primarily in spring, late winter) and mixed events. In contrast the selected stations along the Elbe indicate a comparatively clear seasonality of floods (late winter, early spring) which is more or less the same for all three gauges. Although the analysis points out a tendency to winter (early spring) floods, the most extreme flood events of the period analysed append in summer (August 2002, June 2013)

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In addition to the absolute flood peak, which is used as most important parameter of flood-risk studies, two additional indicators are used here to identify flood events in the study area, which had a relevant impact on IWT:

- Annual days of HSW-exceedance to get an impression of the overall disturbance of waterway transport due to floods.
- The maximum duration of one continuous event leading to suspension of navigation is a suitable indicator for the extremeness of a flood event with regards to IWT. For transportation often not flood events with the highest peak cause the most problems, but those with a long duration (a broad flood wave) leading to a long interruption of water bound transportation. To calculate the maximum duration, a non-exceedance period of 2 days imbedded in a period of exceedance was neglected (2-day-period is assumed to be too short to be used by IWT as in most cases the water-level just falls marginally below the HSW-threshold).

The following figures visualize the above-mentioned flood indicator for the Rhine (Figure 27), the Danube (Figure 28) and the Elbe (Figure 29) for the period 1981 to 2015.

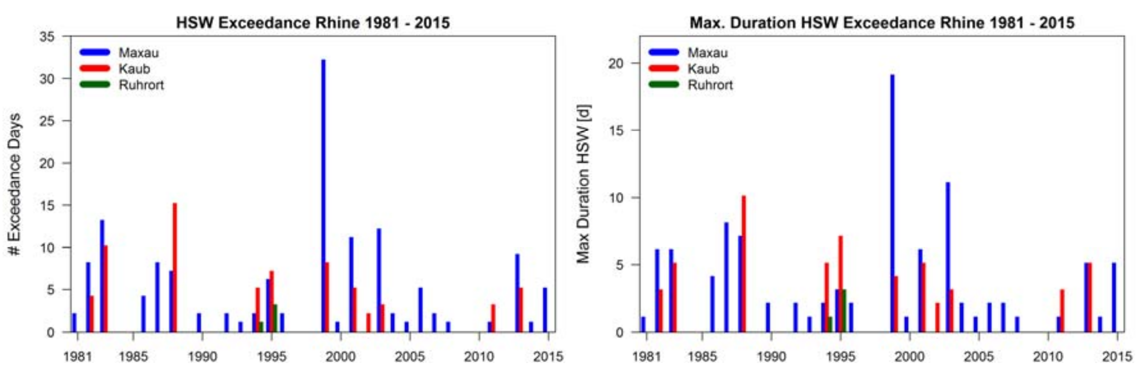

Figure 27: Number of days per year exceeding the HSW-threshold (left) and longest period of HSW-exceedance per year at the waterway Rhine (period 1981-2015)

Within the period analysed HSW was exceeded at the Lower Rhine (gauge Ruhrort) only during the major floods of 1993/94 and 1995, while at Maxau and Kaub this threshold was exceeded more regularly. Maxau is the station with the most exceedance days per year (1999 with more than 30 days) as well with the longest period of HSW-exceedance (1999 with nearly 20 days uninterrupted). At the Danube and at the Elbe also the most upstream gauges Hofkirchen / Dresden show the most frequent as well as the most long-lasting exceedances.

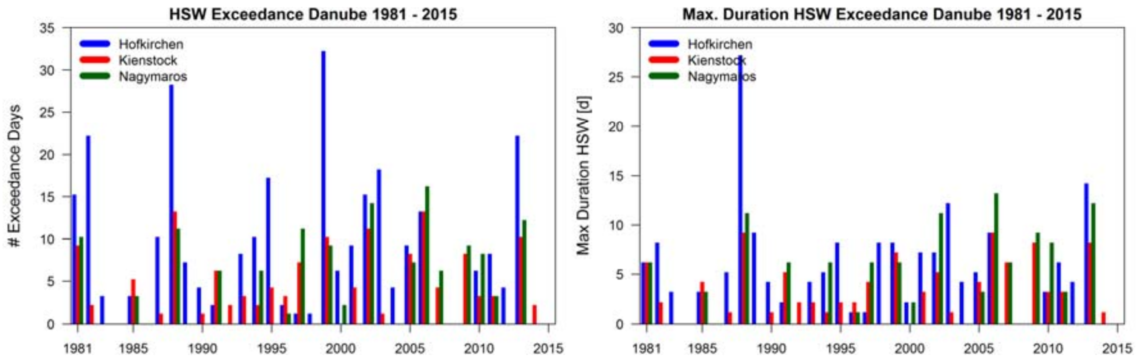

Figure 28: Number of days per year exceeding the HSW-threshold (left) and longest period of HSW-exceedance per year at the waterway Danube (period 1981-2015)

The annual number of exceedance days is slightly higher at the Danube than it is at the Rhine; the maximum duration is similar at both waterways. At the River Elbe (gauges Dresden and Magdeburg) the HSW-threshold was exceeded less often than at Rhine and Danube over the last years (several years with no exceedance).

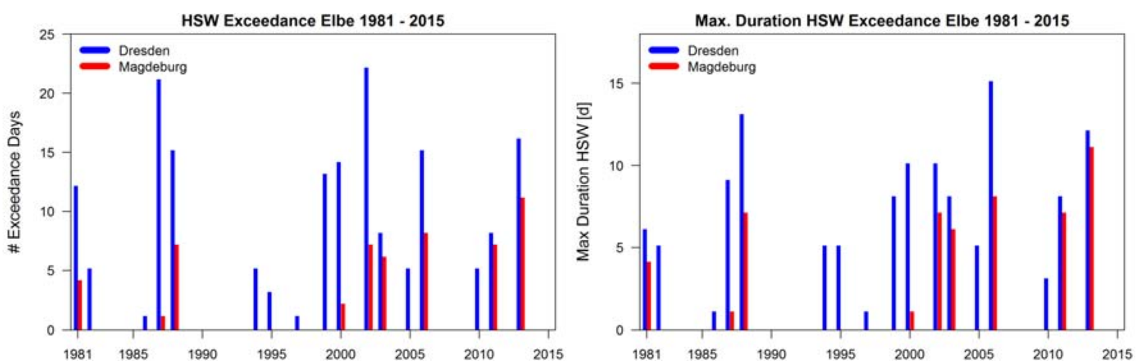

Figure 29: Number of days per year exceeding the HSW-threshold (left) and longest period of HSW-exceedance per year at the waterway Elbe (period 1981-2015)

For the Elbe waterway it is more common that if HSW is exceeded the waterway is closed for several days in contrast to Rhine and Danube where also more short-term suspension of navigation occur over the year.

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To summarize it could be stated that for the considered catchments the following hydro-meteorological conditions lead to extreme high flow events:

- High rainfall amounts for several days over a large part of the catchment. For river Rhine at gauge Cologne e.g. the 10-day antecedent precipitation before the flood has a strong correlation with the flood peaks in winter time (Pinter et al. 2006)
- High antecedent soil moisture conditions in the catchment, as e.g. in the case of the flood 2013 (Ionita et al. 2014)
- Large snow pack accompanied by a rapid temperature rise and heavy rainfall for snow-melt induced floods

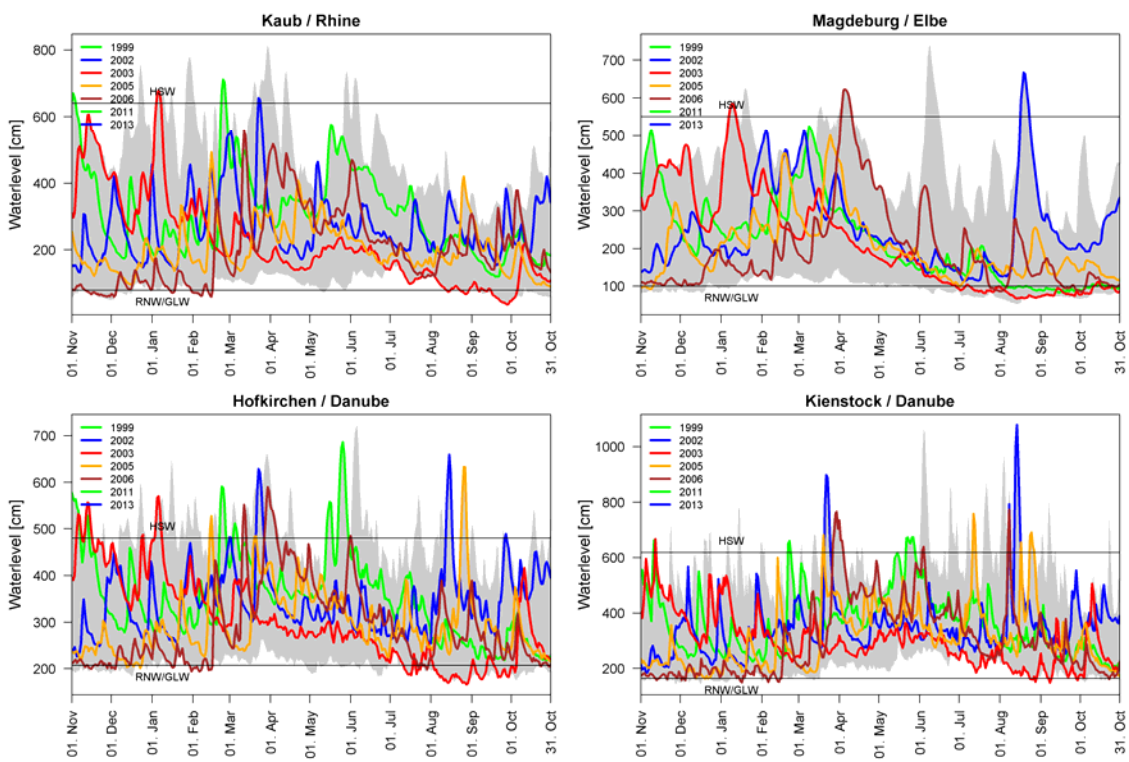

Figure 30: Relevant flood flow years at the gauges Kaub / Rhine, Magdeburg / Elbe, Hofkirchen / Danube and Kienstock Danube. Grey band shows the climatology of the observed daily mean flows of the period 1981-2015.

Based on the aforementioned analysis the following flood events have been selected as the most relevant to IWT. As already mentioned before, the events differ depending on the waterway:

- Waterway Rhine: 1999, 2003, 2011, 2013
- Waterway Danube: 2002, 2005, 2006, 2013
- Waterway Elbe: 2002, 2006, 2011, 2013

Figure 31 shows the hydrographs of these flood flow years for selected gauges.

6.3 Ice

Ice development on canals and rivers is conditioned by continuously low air temperatures over several days plus low flow velocities. These factors are, however, not sufficient to explain the river ice occurrence and thickness. In addition, the heat and salt inflows from power plants and industry play a role. Hence canals and impounded waterway sections are more vulnerable against ice formation than the free-flowing sections of the waterways.

The accumulated total of freezing degree-days (sum of temperatures below 0°C, e. g. between November and March) is often applied as a proxy for the strength of a winter season associated with the disposition for ice formation on standing water bodies (e.g. lakes) (Richards 1964, USACE 2002). Many ice-forecasting techniques depend upon it as a basic tool (see references in Richards 1964, Gauthier & Falkingham 2002). The strength of the winter season depending on the sum of temperatures below 0°C could be classified to (DWD 2016):

- sum < 100: mild winter
- 100 ≤ sum < 200 moderate warm winter
- 200 ≤ sum < 300: moderate cold winter
- sum ≥ 300 : extreme winter

Figure 31 shows that there is a correlation between the sum temperatures below 0°C at Nürnberg in winter and number of days when the Main-Donau-Kanal (MD) is closed due to ice. Also, the stoppage due to ice on the River Main shows a correlation with the temperature in Nürnberg (Nilson et al. 2012).

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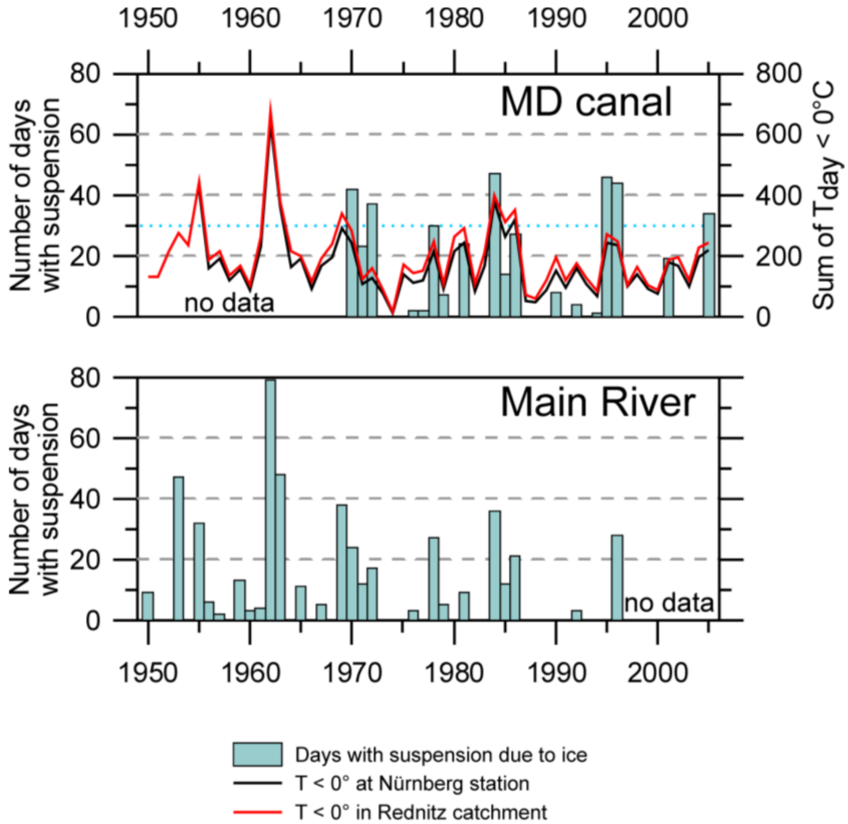

Figure 31: Days with suspension of navigation on the MD canal and the River Main due to ice (Nov-Mar). The top panel also shows the sum of daily temperatures below 0°C (Nov-Mar) in the catchment of the River Rednitz which is used as a proxy for icing in Figure 18. Values above 301 (blue dotted line) are indicative for "extreme" winters (Nilson et al. 2012).

7 Impact of climate change on the vulnerability of inland waterway transport

Main findings:

- Possible climate changes will affect the ease, safety, efficiency and reliability of IWT in the future as investigated in detail, for example, within the research projects ECCONET or KLIWAS.
- The results point towards ambivalent effects of climate change on navigation conditions depending on the period (near future / middle of the 21st century or distant future / end of the 21st century) and the variable under investigation (low flows, floods, river ice).

Possible future changes in climate as indicated by the climate projections of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2013) would lead to changes in the hydrological cycle. These changes will affect the ease, safety, and - thereby - the efficiency and reliability of IWT. The European FP7 project "ECCONET - Effects of climate change on the inland waterway networks" analysed the effect of climate change on the IWT network with a focus on the Rhine-Main-Danube corridor as a case-study, and the interdisciplinary research programme "KLIWAS – Impacts of climate change on navigation and waterways – options to adapt" initiated by the Federal Ministry of Transport (BMVI) integrated aspects of ecology, economy, water quality, and water quantity in order to assess the impacts of climate change on the German federal waterways. The main results of ECCONET on the impacts of climate change on hydrological conditions of navigation summarized in Table 8 are (Nilson et al. 2012):

- Navigation in the Rhine-Main-Danube corridor is to a large degree dependent on climate conditions and therefore affected by climate change.
- The results point towards ambivalent effects of climate change on navigation conditions depending on the period and the variable under investigation.
- During the last decades restrictions of navigation due to low water and ice formation have become less frequent.

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- For the middle of the 21st century there is no clear change in the frequency of low-water situations on the Middle Rhine, while on the Upper Danube several projections show an increase, being however minor.
- For the distant future low-water situations are projected to become more frequent.
- Disposition related to ice formation shows a decreasing tendency over the whole 21st century. This positive effect on navigation does not apply to the River Rhine as there navigation has not been suspended due to ice since the 1960s.
- Restrictions due to high water are projected to become more frequent on the Middle Rhine in the 21st century. On the Upper Danube there are some indications that high-water events will not change very much until the mid of the 21st century. For the distant future, there is currently no clear tendency related to the occurrence of high water, considering available data and literature.
- For future fog conditions there is no clear tendency considering available data and literature.

The results of the research program KLIWAS show the same tendencies for the waterways Rhine and Danube as ECCONET. For the river Elbe the main results of KLIWAS on the impacts of climate change on hydrological conditions of navigation are (Hatz & Maurer 2014, Nilson et al. 2014):

- For the middle of the 21st century there is no clear change in the frequency of low-water situations on the Elbe River, for the distant future several projections show an increase and several projections show no changes in the frequency of low-water situation.
- Low flow situations are not expected to become more extreme in the near future, for the distant future more extreme low flow values are expected.
- There is no clear tendency for a change of high water in the near and distant future at Elbe River.
- It is projected that there will be more moderate winters in Central Europe using the sum of temperatures below 0°C between November and March as indicator. This will lead to a reduction of ice formation on the Central European Rivers and to a decrease of the duration of ice events.

Table 8: Summary of general effects of climate and hydrological change on navigation presented for the second half of the 20th century (tendency 1950-2005), the middle of the 21st century (change 2021-2050 vs. 1961-1990) and the end of the 21st century (change 2071-2100 vs. 1961-1990) (Nilson et al. 2012)

Phenomenon	Period	Middle Rhine	Main-Donau-Kanal	Upper Danube
Low water	1950-2005	positive effect	no effect*	positive effect
	Mid of 21st century	no effect	unknown	negative effect
	End of 21st century	negative effect	negative effect*	negative effect
High water	1950-2005	no effect	no effect	no effect
	Mid of 21st century	negative effect	no effect	no effect*
	End of 21st century	negative effect	no effect	unknown
River ice	1950-2005	positive effect	positive effect	positive effect
	Mid of 21st century	no effect	positive effect	positive effect
	End of 21st century	no effect	positive effect	positive effect
Visibility (fog)	1950-2005	positive effect	positive effect	positive effect
	Mid of 21st century	Unknown	Unknown	unknown
	End of 21st century	Unknown	Unknown	unknown

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8 Forecast products and user needs to mitigate vulnerability of IWT

Main findings:

- Most of the navigation-related forecasts in Central Europe are still deterministic and cover short- to medium-range lead-times allowing for optimizing the load of imminent trips. Probabilistic forecasts allowing risk-based decisions and supporting (more strategic) decisions requiring extended lead-times of several weeks up to several months ahead don't exist at least for the main parts of the trans-European waterway network so far.
- Different types of users along the waterways (skipper, logistic manager, transport operator, waterway manager, transmission grid operator, and economist) and their needs have been identified based on several workshops and interviews, because their knowledge is essential for the future products to be developed within IMPREX and for the customization of those as proper climate services products.
- User needs were also captured by a group model building exercise in which all relevant stakeholders participated and provided their common view of the problems that navigation (with focus on the River Rhine) is having and the ones that might have in the future.
- Navigation-related forecasts, no matter what lead-time, focus on medium- to low flow conditions. Floods and flood forecasts respectively are relevant with regard to the exceedance of navigation-related flood thresholds.
- The main parameter of interest is the water-level (leading to some methodical challenges due to hydro-morphological changes in the river beds).
- Short-term forecasts are still essential in order to practise waterway transport, nevertheless there're a lot of users / applications requiring additional lead-time in order to benefit from hydrological forecasts.

8.1 Current state

Originally navigation-related forecasts have been developed in order to primarily support the individual skipper who aims at maximizing the load of an upcoming trip. Therefore the current lead-times of one to several days usually comply with the travel time of the vessels to pass the main bottlenecks of a waterway leaving the loading port. Those forecasts are used to optimize the load before starting in order to avoid as much as possible that cargo capacity is wasted as well as that the vessel is overloaded. In the latter case the skipper has to wait on the way until water-levels improve or he has to lighter, which means additional costs due to unloading, stocking, further transport via truck or rail etc. Still most of the navigation-related forecasts in Central Europe cover those short- to medium-range lead-times allowing for optimizing the load of imminent trips.

For the German federal waterways deterministic forecasts are published via the River Information Service ELWIS (www.elwis.de) for relevant gauges (see Figure 32). The lead-times of the forecasts vary from waterway to another and also from gauge to gauge at the same river (e.g. Danube and Elbe). The lead-times published are dependent on the quality of the forecast. Two types of forecast qualities are distinguished:

1. "Vorhersage" (Forecast): 80% of the forecast errors have to be in the interval -10cm to +10 cm
2. "Abschätzung" (Trend): 80% of the forecast errors have to be in the interval -20cm to +20 cm

For the waterway Rhine forecasts are published for all gauges with a lead time of 4 days (day 1 to 2 "Vorhersage", day 3 to 4 "Abschätzung"),. For the waterway Elbe the lead times range from 2 days at gauge Usti in the Czech Republic (first day "Vorhersage", second day "Abschätzung") up to 8 days at gauge Neu-Darchau (day 1 to 4 "Vorhersage", day 5 to 8 "Abschätzung").Ffor the waterway Danube (German stretch) the lead times range from 2 days at gauge Pfelling (first day "Vorhersage", second day "Abschätzung") up to 4 days at gauge Vilshofen (day 1 to 2 "Vorhersage", day 3 to 4 "Abschätzung").

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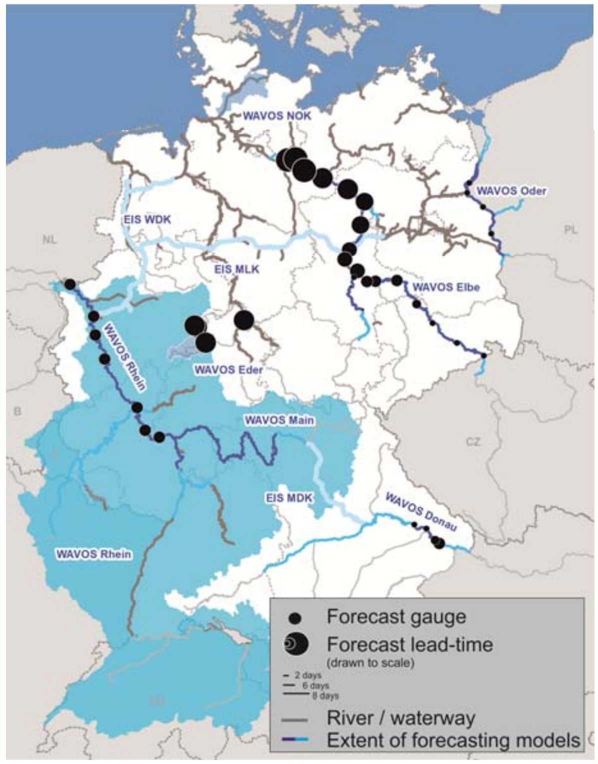

Figure 32: Lead-times of navigation-related forecasts for the German waterways (status 2016)

The current water-level forecasts for Lobith, the most upstream gauge at the Dutch stretch of the Rhine waterway, also has a lead-time of 4 days and is published via the Fairway Information Service of Rijkswaterstaat. For the Austrian part of the Danube forecasts for the two gauges Kienstock and Wildungsmauer, which are representing relevant bottlenecks (see Figure 3), are published via the Danube River Information Services DoRIS if the current water-levels drop below mean-water. The lead-time of these forecasts is 72 hours (like the one for Hofkirchen, representing the main bottleneck along the German part of the Danube). In addition to the deterministic "best-guess" - forecast a confidence interval, representing the uncertainty of the hydrological model as well as the meteorological uncertainty, is already shown. This is the case for the Hungarian gauges at the Danube, too. The lead-forecast is surrounded by an "error interval", which is mainly based on statistics. Forecasts for more than 15 gauges along the Danube are published on a regular basis covering a lead-time of 6 days.

Despite the examples of Hungary and Austria still most navigation-related forecasts are deterministic. So, the forecast provider usually don't offer an objective estimation of the inherent forecast uncertainty (even for short lead-times), but each user has to do this individually, mainly based on his experience with the hydrological systems as well as the forecasts. Without publishing the predictive uncertainty of the forecast, rational decision-making on issues such as maximum vessel load based on objective cost-benefit analysis isn't possible. Within IMPREX it is planned to demonstrate the added economic value of probabilistic forecasts for IWT. To quantify the impact of improved forecasts on transportation costs monetarily a cost structure model is applied to the water level forecasts.

For Germany (Hemri et al. 2015, Klein et al. 2015, Klein et al. 2016) and the Netherlands (Verkade 2015) probabilistic short to medium term forecast systems are in development but they are not operationally yet.

Furthermore the lead-times mainly cover the short- to medium-range with the majority of lead-times between 3 to 6 days. Forecasts supporting (more strategic) decisions requiring extended lead-times of several weeks up to several months ahead don't exist at least for the main parts of the trans-European waterway network so far (status: mid of 2016). Without doubt the existing (short- to medium-range) forecasts are extremely valuable for many waterway users (mainly skippers just focussing on the optimal load capacity of their current trip). But in the light of the increasing need to integrate IWT into multi-modal transport chains and the overall tendency to increasing vessel sizes, additional lead-time going beyond an imminent trip is needed by different waterway users. In the next chapter the user needs on extended forecast products are identified. The lead-times defined in this section are requirements of IWT on the respective forecast product to support their decisions. At this stage the lead-times are not linked to a forecast skill yet. The required skill of the forecast product to affect decision making as well as the achievable preciseness have to be discussed within the stakeholder process of IMPREX.

At the moment the forecast information used to support long-term decisions are the observed water-level / flow climatology. Each new forecast products showing a better skill for the required lead-time than the climatology have an added value compared to the information used today.

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8.2 User needs

In order to identify the user requirements of new forecast products offering extended lead-times workshops and interviews with different stakeholders have been conducted. The stakeholders selected represent different sectors of waterway users all interested / dependant on the "wet" mode of transportation: shipping companies / logistic companies ("carrier", executing the transports on the waterways), industrial enterprises ("consignor", dependent on waterway transport to carry relevant raw materials / products), transmission network operators (ensuring availability and stability of electricity), administrative authorities / ministries (being in charge of waterway management and maintenance) and intergovernmental organizations (promoting / strengthening of waterway transport in the field of the European transport policy). The following types of users have to be considered when in the design of forecast products:

The **skipper** is responsible for the save execution of the particular transport. Therefore it is the skipper (and not a logistic manager) who has to account for the maximum load to be carried in the end. The skipper also has to decide if e.g. lighterage is necessary to pass a specific stretch of the waterway. Skippers are usually keen on having real-time information on the measured water-levels along their route as well as short-term (several days ahead) forecast information on a regular basis for relevant (load-determine) gauges. On the River Rhine, for example, it takes 3 to 4 days to pass the main bottleneck between St. Goar and Mainz when starting at the port of Rotterdam. The majority of skipper has a multi-year experience on the behaviour of the river they are sailing on and they usually combine their subjective assessment with the "official" water-level forecast. Based on their experiences they know that hydrological forecasts (even on the short-term) are uncertain, but correct understanding and use of explicitly communicated forecast uncertainty would require explanation / training in most cases.

Logistic managers are mainly concerned with trading capacities of transporting at a given supply and demand to make profit. They usually work for bigger logistic companies which focus on water-bound transport, but usually offer the whole transportation chain (including also other transport modes, e.g. road). This task, especially the integration of waterway transport into multi-modal transportation chains, is quite complex as a lot of influencing variables (one of these variables is the expected water-level situation along the waterways) have to be taken into account. Therefore water-level forecasts are intensively used in the day-to-day business. Although there is also a short-term trade of shipping space, the main interest of the logistic manager is the medium-range (several weeks ahead) and the monthly to seasonal time-scale as their more strategical decisions require longer lead-times than those of a skipper. The earlier and the more accurate the logistic manager could anticipate the hydrological situation, the better his decisions would be. Typical decisions of the logistic manager are the determination of the timing of transports to minimize costs or to handle extremely heavy / large goods or to deliver goods arriving via maritime vessels in an optimal way (timing, costs). Logistic managers have a general understanding of forecast uncertainties and they are well-trained to take risk-based decisions.

Transport operators (at a factory) are the counterpart of the logistic managers as they book shipping space in order to supply raw material necessary for the factory (or power plant) to produce goods (or energy) as well as to transmit the final products. Taking into account the available storage capacity the primary duty of the transport operator is to avoid reduction of the manufacturing process due to insufficient raw material feed or spilling over of warehouses and to minimize transport costs at the same time. The typical lead-times required by transport operators are the medium-range up to the monthly time-scale in order to shift cargo from shipping to another mean of transportation in case of low flows, to build up stocks (e.g. refineries) or to hire additional storage space for industrial goods (interim storage facility). Large factories sometime employ hydrologists / meteorologists in order to produce, communicate or optimize tailored in-house forecasts. But despite of those hydrologists the transport operators have a sound understanding of the system and the related uncertainties and as the logistic managers they are well-trained to take risk-based decisions.

Waterway managers are responsible for the regulation and preservation of waterways and therefore for the ease and safety of the waterway transport. They continuously monitor the riverbed by bathymetric surveys to get an overview about the problematic areas and operate continuous water level measurement gauges. Based on the bathymetric surveys measures for the maintenance of the fairway are planned and dredging as well as adjustment of the fairway is executed. Usually dredging measures are operated by external companies based on long-term contracts. Overall information about the fairway conditions

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and restrictions and forecasts about the expected water levels in the next days are provided via River Information Services RIS. To optimally plan bathymetric surveys waterlevel forecasts with a lead time of 4 to 7 days are used by the waterway managers at the moment. Shallow areas in morphological active sections of the river are highly dependent on the flow conditions. High flows could reallocate sediments and reduce the shallow sections due to the high flow velocities. Medium-term and monthly forecasts could be highly valuable to effectively plan and allocate dredging measures and resources or even to avoid dredging measures when high flows are expected in the next month. Waterway managers know there system very well and have a general understanding of forecast uncertainties.

Transmission grid operators are responsible for operating, maintaining, planning and expanding the electric transmission network. They maintain the balance between power generation and consumption within their control area. A fast response to incidents that threaten the network's stability, and to supply/demand imbalances, is essential. One method of preventing critical situations within the grid is redispatch: rapidly adapting the scheduled output of power plants in line with current demand to prevent overloads. To achieve this goal transmission grid operators collaborate with power plant operators, other transmission grid operators and other market participants to stabilise the transmission network. Transmission grid operators use control energy to offset any deviations from the agreed power supply. This control power capacity has to be available at any time. In the case of long-lasting low flow events with reduced inland waterway transport the available coal storage of power plants could become critical, as it was e.g. the case during the low flow event 2015. Water level measurements and forecasts are used to monitor the situation and in extreme cases to plan and execute measures to guarantee control energy capacity. Long-term forecasts could be used as a pre-alert system to prevent critical situations due to extreme low flow situations. Transmission grid operators normally don't have a hydrological background, so any forecast information has to be tailored and interpreted to be useful to their decision making.

Economists are e.g. working for the central commissions of navigation to promote inland waterway transport. They observe and monitor the market and the general economic situation of inland waterway transport. They provide outlooks about the future development of transported goods. In case of the CCNR (Central Commission for Navigation on the

Rhine) this activity has become part of a much wider project for observation of the market, carried out in partnership with the European Commission. As expected future flow conditions, which influences the consumer demand of transport volumes as well as the cargo rates / prices, observed climatology is considered in these outlooks at the moment. Medium-term to seasonal flow forecast products have great potential to improve the expected flow evolution and therefore the predicted transport volumes within the outlook. Economists normally don't have a hydrological background, so any forecast information has to be tailored and interpreted to be useful to their decision making.

User needs were also captured by a group model building exercise in which all relevant stakeholders participated and provided their common view of the problems that navigation (with focus on the River Rhine) is having and the ones that might have in the future (see Figure 33).

Figure 33: Group Model Building Exercise in Koblenz, 11th April 2016

The knowledge of the participating stakeholders is of high interest for the future products to be developed within IMPREX and for the customisation of those as proper climate services products. During the exercise (see Figure 34) not only the different views of individuals participating were synthesised but also their needs and perceptions of environmental risks.

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Figure 34: Group Model – set-up during the stakeholder workshop on 11th April 2016

Table 9 summarizes the user need identified so far of the different waterway users and describes the corresponding decisions requiring additional forecast lead-time. It's obvious that short-term forecasts are still essential in order to practise waterway transport, nevertheless there're a lot of users / applications requiring additional lead-time in order to benefit from hydrological forecasts and support decision making. The required associated skill of forecast products with extended lead-time to affect decision making as well as the achievable preciseness have to be discussed within the stakeholder process of IMPREX.

Despite the last forecast-based decision mentioned in Table 9 ("reduction of dredge operations") all other users / applications require water-levels as forecasted parameter instead of flow rates. On the one hand this might also be a matter of habit, but on the other hand the water-depth, which is directly related to the water-level, is the parameter the users are working with in their day-to-day business. The disadvantage of the variable water-level, compared to flow rate, is that it is highly dependent on the river morphology at the specific gauges. Depending on the geological situation the river morphology could be quite dynamic, so that hindcasting over a longer period might be affected by morphological changes which the forecast system / forecast model has to take into account. Fore purely statistical methods those morphological changes are even more challenging as they lead to an inconsistent data basis for training the model as well as to a limited predictable value for the future. There are different ways to generate water-level forecast: Typically in a short- to medium-range forecasting system a hydrodynamic model is used to directly calculate water-levels based on flow rates and the river morphology / shape. As those models are computationally demanding compared to e.g. hydrological models, it is a common procedure, especially for medium-range to long-term forecasts, to use (non-linear) rating curves (stage-flow-relationship) to translate calculated flow rates into water-levels. A third option using purely statistical forecasting models is to train those models directly on measured water-levels.

As described in chapter 1 low stream flow is the main hydrological impact on the efficiency of IWT. Therefore navigation-related forecasts, no matter what lead-time, focus on medium- to low flow conditions. Floods and flood forecasts respectively are relevant with regard to the exceedance of navigation-related flood thresholds (HSW I, HSW II). The navigational users are interested if and when such a flood threshold might be exceeded (as navigation is prohibited in this case) and how long such a shipping ban will last. The absolute height and timing of the flood peak is of minor interest.

The required forecast frequency is comparatively low e.g. by contrast with flood forecasts. As the latter ones are published several times per day up to every hour (normally depending on the size of catchment) current navigation-related forecasts are often issued just once at maximum twice a day. Of course, the water-levels / flow rates in low to medium flow periods are far less dynamic as during floods, especially at the larger waterways like the River Rhine (the forecast gauges represent catchments of tens of thousands of square kilometres.

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Table 9: User needs of the different waterway users, corresponding decisions requiring additional forecast lead-time

	Required Lead-time of forecast product(s)			
	short-range (≤ 7 days)	medium-range (≤ 14 days)	monthly (≤ 1 month)	seasonal (≤ 3 months)
Transport / logistic companies (carrier)				
Optimization of current vessel load	x			
Shifting cargo from shipping to another mean of transportation in case of low flows		x	x	
Scheduling of a complete transport cycles (up- and downstream trip)		x		
Optimized deliverable of goods arriving via maritime vessels		x	(x)	
Scheduling of special transport (heavy / large load)		(x)	x	
Optimized timing of transports to avoid additional costs in case of low flows		(x)	x	x
Adaption of fleet / usable transport capacity			x	x
Industrial companies (consignor)				
Shifting cargo from shipping to another mean of transportation in case of low flows		x	x	
Building up stocks (e.g. coal power plants, refineries etc.)		x	x	
Hire additional storage space for industrial goods (interim storage facility)		x	x	
Guarantee security of energy supply (Redispach)		x	x	
Waterway management				
Planning / Timing of measurement projects	x	x	(x)	
Timing / suspending of dredge operations	x	x		
reduction of dredge operations	(x)	x	x	

9 Conclusion

Inland Waterway Transport (IWT) is a means of transportation and accordingly an important commercial sector significantly vulnerable to hydrological impacts. While other modes of transportation (road, railway, air traffic) are practically only affected by (comparatively rare) hydro-meteorological extremes, IWT shows a permanent interaction with hydro-meteorological impacts, not solely with extremes. Its outstanding vulnerability is primarily caused by the close correlation of the IWT's operation efficiency and the water-depths along the major waterways, which vary (except for canals, impounded river stretches) due to the hydro-meteorological conditions and its seasonality. Despite regional differences in the catchment (e.g. elevation, geology, soils, underground reservoirs etc.) and in the waterway characteristics (e.g. maintained water-depths, waterway class) as well as in the hydro-meteorological conditions (hydro-climatic regime) low flows are regarded as the major threat to the reliability and efficiency of IWT in Central Europe. From the navigational perspective floods are in general more harmful to the waterway infrastructure (possible damage to navigation signs, gauges, ramps, groynes etc.) than to waterway transport itself. Low flow situations, however, occur regularly and they are relatively long lasting (weeks or even months). Low flows cause low available water-depths in the rivers leading to increasing transport costs which deteriorates IWT's competitive and favourable position compared with other modes such as road and railways.

The analyses presented in this report provide the basis for further target-oriented research and development for the waterway transport sector within IMPREX in many ways. The study area covers the large inland waterways and the corresponding hydrological catchments of the River Rhine (one of the most-frequented waterways worldwide), the River Danube up to gauge Nagymaros in Hungary and the River Elbe:

- The critical locations (current "bottlenecks") along the different waterways in Central Europe and their corresponding gauges have been elaborated in order to put a specific focus on them for the evaluation of improvements achieved by IMPREX.

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- The report identifies relevant extreme events (floods and low flows) of the last 15 years for which the results of improved forecasting models and methods within IMPREX should be validated.
- The vulnerability of IWT due to hydro-meteorological impacts has been analysed, which forms the scientific basis for the use of a cost-structure model approach during the future project stages.
- The impacts of possible future changes in climate on the hydrological conditions / parameters relevant for navigation have been allocated based on former studies usable as baseline for potential analysis within IMPREX.
- In cooperation with current forecast users, potential users and stakeholders representing logistic companies, industrial enterprises, transmission network operators, waterway management authorities / ministries and intergovernmental organizations,
    a) short-comings of current navigation-related forecast products have been identified and
    b) attributes of future forecasting products have been defined in order to mitigate vulnerability of IWT due to hydro-meteorological impacts on different time scales (short-term up to seasonal).
- The group model building exercise gives basis for the development of an integrated model with which stakeholders can test different decisions based on the improved climate forecast for different water-levels involving the complex feedback loops and implication that a particular decision might have. The integrated and customised model will be further developed in the IMPREX work package 13 and will be tested and validated together with the users in the coming months. First part of these results will be presented in deliverable 13.1 in which all information obtained and synthesise for this deliverable will flow in.

Hydrological forecasts with a specific focus on water bound transport (relevant locations, parameters, skill characteristics etc.) will play a major role in order to mitigate IWT's vulnerability due to hydro-meteorological impacts. This is an essential prerequisite to increase the efficiency of IWT and to stimulate the use of the free capacity inland navigation offers more consequently. In light of continuing transport growth within the European Union there is a need to release the already overloaded road and railway networks and to strengthen IWT as a safe and environment-friendly mode of transportation. Besides a good waterway infrastructure an optimized and anticipatory handling of the dominant natural / hydrological impacts on inland navigation is required – IMPREX will try to contribute in this regard, too.

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